A N N U A L   R E P O R T

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U. S. WATER CONSERVATION LABORATORY
U. S. Department of Agriculture
Agricultural Research Service
Western Region
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Phoenix, Arizona 85040

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Struckmeyer, Jaime	Biological Aide
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TITLE: SEEDLING ESTABLISHMENT OF NEW CROPS UNDER CRUSTING AND OTHER LIMITING RELATED CONDITIONS

SPC: 1.2.03.1.a
2.3.04.1.n

CRIS WORK UNIT: 5344-12230-001

INTRODUCTION

The introduction for this CRIS was presented in the 1986 Annual Report. It pointed out the need for - and difficulties encountered in - direct seeding of guayule and other small-seeded new crops.

Figure 1 is a list of some of the factors involved in the establishment of guayule - or most crops . All the factors relate to obtaining good seed; then making that seed perform optimally to obtain the established crop. The factors are categorized into seed, site/seeding, and post-seeding factors. Seed factors start with selection of the crop; then go on to seed selection and/or breeding, and include various natural and controllable factors that assure top quality seed at harvest. Optimization of the seed also includes seed-house and laboratory procedures to enhance the vigor, quality and performance of the seed. Site/seeding factors involve selecting and preparing the site and the actual seeding operation. For small seeded crops like guayule these factors are critical to crop establishment.

The post-seeding factors listed in Fig. 1 have been separated into the three phases of germination, emergence, and establishment. Most of the germination factors relate back to prior seed and soil preparation practices. If the crop is irrigated, one has a greater measure of control over water, salt, and temperature stresses to enhance germination. Most of the factors shown which affect germination also affect emergence. Soil crusting can be an added problem decreasing emergence. For most crops the transition from seed power to sun power (emergence to establishment) occurs without problems. Guayule, unfortunately, is extremely vulnerable during this period: the transition is prolonged and the young seedlings are inordinately vulnerable to pests and diseases during that growth stage.

Of course Fig. 1 is only a partial list of factors; e.g.,the types of additives which have been proposed to enhance the seed or to improve the soil is practically boundless. The underlined factors in the Fig. 1 are those which have been evaluated in varying degree under this project and/or in cooperation with Dale Bucks in several field-seeding operations. The multitude of factors involved in establishment and the relative unknown importance of each when working with a new crop makes modeling extremely difficult.

Field studies

Results of the first field experiment on direct seeding under this CRIS were presented in the 1986 Annual Report. It showed that 5-mm-deep planted guayule had higher emergence and survival, than surface planted seed, and that establishment was extremely sensitive to moisture stress.

In 1987 these studies were continued to optimize planting depth; compare conditioned vs. raw seed, evaluate two soils types, compare seed covers of different densities, and optimize irrigation scheduling during the germination and emergence growth stages.

MATERIALS AND METHODS

Four experiments were carried out on two 24 by 2.5 m^2 outdoor plots at the USWCL in 1987. The sand plot was washed, Salt River bed, fine sand in a 2-m-deep plastic-lined pit. It was the plot used in the preliminary experiment described in the 1986 Annual Report. The soil plot was the on-site Avondale loam.

Prior to each experiment the particular plots to be used were rototilled, smoothed, wetted, and lightly rolled. Air and soil temperatures were recorded using imbedded thermocouples. Four drip lines were installed on each plot; each line either represented a replication with treatments randomly scattered along each line (Exps. 2 and 3), or else constituted a separate irrigation treatment (Exps. 4 and 5). The seed was raw or conditioned guayule cv. 11591, planted dry; i.e., not pregerminated. Planting was done as in Exp. 1, by punching holes or slots in the soil to the desired depth. Seeding rate, unless stated otherwise, was 100 seeds per 2 m row length for singulation, and 10 seeds per clump, 20 clumps per 2 m row length for clumping. Each experiment was replicated 4 times. Stand counts were taken daily until maximum emergence; then periodically thereafter until the stand was essentially stabilized — generally one month. Insects were controlled by broadcasting Spectracide on the plots as needed.

Exp. 2. Variables: Two soils (sand and Avondale); 4 planting depths (0, 5, 10, and 15 mm); two planting modes (singulate and clump); and 2 covers atop the seed (soil from each respective plot and expanded vermiculite). Only conditioned seed and one irrigation regime were evaluated. Planting date was Mar. 4, 1987. Plots were irrigated each day for 10 days straight to keep the soil continually wet; then weekly until the close of the experiment on day 62.

Exp. 3. Variables: Four planting depths (5, 10, 20, and 30 mm); raw and conditioned cv. 11591; and 2 covers atop the seed (soil and vermiculite). Only Avondale soil,the singulation planting mode, and one irrigation regime were evaluated. Planting date was May 26, 1987. Planting rate was 200 seeds per 2-m-long treatment. Plots were irrigated each day for 8 days straight; then periodically for the remainder of the month.

Exp. 4. Variables: The same two soils; 4 planting depths (5, 10, 15, and 20 mm); and 4 irrigation regimes (all treatments received 14 mm immediately after planting; then approximately 5 mm: -every day, -every other day, -every fourth day, and -every sixth day). Only conditioned 11591, the singulation planting mode, and the vermiculite seed cover were evaluated. Planting date was Sep. 17, 1987.

Exp. 5. Variables: The same two soils; 4 planting depths (5, 10, 15, and 20 mm); and 4 irrigation regimes (all treatments received 13 mm immediately after planting; then were irrigated as in Exp. 4). Only conditioned cv. 11591 (same batch of seed as used in Exp. 4), the singulation planting mode, and the vermiculite seed cover were evaluated.

RESULTS

Exp. 2. The primary purpose of the second experiment was to determine the optimum seeding depth for guayule. The 1986 experiment had shown that 5 mm deep was better than surface plantings, but possibly, deeper depths were better still. Tables 1a and 1b list stands at maximum emergence and on day 30 (both adjusted for laboratory germination of 72%) for the sand and Avondale soils, respectively, and for singulated and clumped planting modes. With singulation, the best emergence (91%) and 30-day stands (82%) were both obtained from the deepest planting (15 mm) of vermiculite-covered Avondale soil. Both maximum emergence and established stands for this treatment increased with planting depth (Fig. 2). In general, the surface plantings had lower emergence and greater die-off than the 3 deeper plantings, regardless of soil type or seed cover.

Tables 1a and 1b also show the number of days to 95% of maximum emergence. This value is more consistent than days to maximum value, and may be useful for scheduling irrigations and other agronomic practices. As expected, the number of days to 95% maximum emergence increased with greater planting depth, but the pattern was not regular. Rapid emergence reduces risks and speeds the transition from seed-power to sun-power, but planting too near the surface to speed emergence may expose the seed to undue water, salt, and temperature stresses.

Clumping the seeds produced results similar to those with singulation: deeper plantings were better than surface planting. Some treatments produced near perfect emergence and established stands (99 and 92%, respectively). Values refer to clumps, not individual plants. Clumping and singulation both produced adequate stands in this study; clumping, however, may have advantages under less favorable planting conditions.

Exp. 3. The purpose of this study was to compare the emergence and survival of conditioned vs. raw guayule seed at different planting depths and with different seed covers. The conditioned seed emerged quicker than the raw seed (Table 2). Under irrigation conditions this means that less water is required to get the crop up and that risks to the vulnerable young plants during the critical germination and emergence phases are reduced. Clearly, some treatments in Exp. 3 were planted too deep. Except for the vermiculite-covered, conditioned seed, one would conclude that guayule should be planted only 5 mm deep — or shallower. This concurs with many earlier recommendations. However, these studies suggest that conditioned seed can be planted deeper: 10 or even 15 mm appears to be optimal. It is reassuring to know that good emergence will occur over a range of planting depths, since field planting is never an exact operation.

The ratio values at the bottom of Table 2 show that the vermiculite seed cover enhanced emergence. The ratio of highest to lowest maximum emergence in each column shows that vermiculite-covered seed had ratios of 1.7 and 3.2 for conditioned and raw seed, respectively, but for soil-covered seed the respective ratios were 6.7 and 19.3. Vermiculite covering tends to be forgiving of planting the seed too deep.

The ratios of best and worst maximum emergence values at each depth, shown in the right hand column of Table 2, increase with depth, ranging from only 1.5 at 5 mm to 19.9 at 30 mm. The implication is that if you are planting low vigor seed, particularly under unfavorable conditions, it is best to plant shallow. This also conforms with most published findings.

Table 2 also shows the one month stands and the losses over that period. The best treatment lost about one-fourth the plants, which is reasonable for guayule. But 6 treatments lost over 50%. These high losses are thought to relate to the high temperatures during establishment for this experiment; May-June may be too hot to establish guayule in Arizona. Nevertheless, it may be possible to do it by using conditioned seed, planting 10 to 15 mm deep, covering with vermiculite, and increasing the seeding rate as needed.

Exp. 4. The results of the four irrigation regimes on emergence and establishment of conditioned guayule seed planted in September are shown in Tables 3a and 3b. The shallow 5-mm plantings generally had poor emergence regardless of the irrigation regime. The wet, 5-mm-deep planting on Avondale soil is a possible exception, even though 50% emergence is still rather low. The dryer irrigation regimes produced lower stands throughout on the sand but not necessarily on the Avondale. The deeper 15- and 20-mm plantings fared better than the shallow plantings. Stand losses, the first month were very large for all irrigation regimes on the Avondale soil, but were reasonable on the three wettest regimes on the sand.

Exp. 5. The emergence/stand data appear in Tables 4a and 4b, and Fig. 3. In general, the time required for 95% of maximum emergence increased from 4 or 5 days at the 5 mm planting depth to 7 or 8 days at the 20 mm depth, and emergence on the Avondale soil was a day or more ahead of that on the sand. There was no consistent difference in 95% maximum emergence time as related to the 4 irrigation regimes, which suggested that little was gained in that regard by irrigating every day. In general, the 10- and 15-mm depth plantings had greater maximum and 30-day stands than those planted at the 5 and 20 mm depths. On the sand, the shallow 5 mm deep planting consistently had the lowest 30-day stands, and as irrigation frequency decreased the stands on deeper planted seed improved relative to shallower plantings. The data suggest that it is not necessary to irrigate guayule every day during the germination/emergence phases. The best approach for singulation planting of guayule may be to plant 10 to 15 mm deep, cover the seed with vermiculite, irrigate the first two days, and then switch to a dryer irrigation schedule of once a week or so. This needs verification. It probably is dependent on soil and weather conditions. It is assumed that the seed is conditioned and that soil crusting is prevented.

Fig. 3 shows a rapid decline in stand shortly after maximum emergence and then a gradual increase, which varied according to planting depth. This increase looks like it might be related to the 31 mm rain on day 11, but probably relates more to the gradual revival of severely insect damaged plants as the weather cooled and insect populations drastically declined the first week of November.

Even though Exps. 4 and 5 were set up identically, the emergence/stand results were radically different. In Exp. 5, planting at 10 to 15 mm deep would almost assure a 30-day stand in excess of 50% (adjusted for laboratory germination), regardless of the 4 irrigation schedules. With Exp. 4, however, only the wettest, 10- and 15-mm deep plantings on the sand plot had 30-day stands as great as 50%. Most Exp. 4 stands were one-half to one-fourth as great as in Exp. 5, and many treatments in Exp. 4 lost more than 25% of the stand between maximum emergence and day-30.

These differences in stands between Exps. 4 and 5 may be due partially to insect damage. Insect populations dropped off radically shortly after the plants in Exp. 5 began to emerge. Temperature differences, however, during the course of the experiments may be a bigger factor. Figures 4a and 4b show one-month adjusted stands for the several planting depths vs. the average of daily average temperatures during the first 7 days following planting for the four experiments detailed here. Guayule appears to prefer cool temperatures during establishment. Results seem reversed between Exps. 3 and 5 on the Avondale soil, but Exp. 3 was planted in May when temperatures were rapidly increasing, while Exp. 5 was planted in October when temperatures were rapidly decreasing. The data in Figs. 4a and 4b suggest that early spring, as soon as danger of frost is past, may be the best time to plant guayule in the Phoenix area. An added advantage of an early spring planting is that insect populations are still low then.

CONCLUSIONS

The findings from these experiments suggest several ways to improve emergence and stand establishment of direct-seeded guayule under irrigated conditions. Optimum planting depth for conditioned seed for most experimental conditions studied here was 10 mm. Raw seed, however, performed better if planted only 5 mm deep. Surface planted or slightly covered seed gave low emergence and survival stand counts. Seed conditioning shortened and unified seedling emergence, and appeared to inordinately improve the vigor of the weak and inhibited seed.

Use of expanded vermiculite covering atop the seed, rather than soil, also hastened emergence, allowed weaker seedlings to emerge, circumvented soil crusting, tended to be forgiving of deep and uneven planting, and in general, reduced planting risks. Shallow-planted guayule, however, performed better with a soil covering than with vermiculite. Planting guayule as deep as practicable, then covering the seed with vermiculite, also saved water, since daily irrigations during emergence were not necessary to prevent crusting.

Emergence and stand establishment were affected by the season of planting. A March planting produced emergence and 30-day stand counts (adjusted for laboratory germination values) in excess of 90 and 80%, respectively, for several singulated treatments. Stands from a hotter late May planting generally were less than half that of the March planting. An even hotter mid-September planting had even lower stands.

By using clumping in seed placement, we attained nearly 100% emergence for some treatments in the March planting. Clumping permitted closer control of plant spacing and hastened emergence, compared to singulation planting. Due to competition, individual plants in the clumps were smaller than average singulated plants. Under the conditions of these experiments, the planting rate of 10 seeds per clump was excessive.

Emergence and established stands were highly dependent on water, temperature, and salt stress. Temperature stress, as already pointed out, relates to planting season. Regarding water, it appears that conditioned guayule seed needs to be under saturated of near-saturated soil conditions for at least the start of the germination process. Our results showed, however, that increasing water stress after emergence improved both plant growth and survival.

The results of these studies suggest that emergence and stand establishment can be improved by planting deeper than previously, generally recommended. One can best accomplish this by using conditioned seed and covering it with a light porous covering such as vermiculite. Planting deep normally provides a more favorable and stable soil environment for the seed than that which exists near the soil surface. Surface crusting would nullify these findings, but was circumvented in these studies by keeping the soil moist until maximum emergence had been attained and/or by covering the seed with expanded vermiculite. Early spring (March and April) seem to be the preferred time of the year to plant guayule in the Phoenix area.

PERSONNEL

D. H. Fink

Table 1a. Maximum emergence and stand reduction by day 30 for the Avondale soil (planted 4 Mar. 1987)[1/]

Treatment		Singulated					Clumped				
		Maximum emergence			Established stand		Maximum emergence			Established stand	
Seed cover	Seed depth	Stand	Time	95% max.	Day 30	Loss	Stand	Time	95% max.	Day 30	Loss
-	mm	%	Days	Days	%	%	%	Days	Days	%	%
Soil	0	69.0	13	9.2	27.6	60.0	96.2	9	6.3	86.2	10.4
	5	90.2	15	9.4	64.9	28.0	97.5	8	5.0	87.5	10.3
	10	80.1	19	9.3	62.0	22.6	97.5	9	7.1	82.5	15.4
	15	83.8	15	11.9	72.5	13.5	87.5	9	7.5	75.0	14.3
Vermic-ulite	0	38.7	15	10.0	22.9	40.8	81.2	8	6.2	67.5	16.9
	5	66.3	15	9.5	43.8	33.9	98.8	5	4.9	90.0	8.9
	10	76.8	15	9.5	69.0	10.2	97.5	7	5.9	92.5	5.1
	15	90.9	15	11.5	81.5	10.3	97.5	13	7.7	92.5	5.1

1/ Singulated stand values were adjusted by dividing by the laboratory-determined germination (0.72).

Table 1b. Maximum emergence and stand reduction by day 30 for the sand soil (planted 4 Mar. 1988).[1/]

Treatment		Singulated					Clumped				
		Maximum emergence			Established stand		Maximum emergence			Established stand	
Seed cover	Seed depth	Stand	Time	95% max.	Day 30	Loss	Stand	Time	95% max.	Day 30	Loss
–	mm	%	Days	Days	%	%	%	Days	Days	%	%
Soil	0	56.3	9	8.1	37.0	34.3	76.2	8	7.0	65.0	14.7
	5	80.5	9	8.0	63.3	21.4	85.0	9	7.0	81.2	4.5
	10	78.4	12	9.9	73.4	6.4	98.8	8	7.0	92.5	6.4
	15	52.3	12	10.9	46.9	10.3	93.8	12	7.9	83.8	10.7
Vermic- ulite	0	25.6	9	8.4	8.1	68.4	38.8	9	8.0	18.8	51.5
	5	67.1	9	8.0	55.2	17.7	85.0	6	5.1	63.8	24.9
	10	67.3	12	10.0	57.9	14.0	98.8	7	5.5	92.5	6.4
	15	72.1	12	10.6	57.2	21.7	98.8	9	7.3	85.0	14.0

1/ Singulated stand values were adjusted by dividing by the laboratory-determined germination (0.72).

Table 2. Emergence/stands of conditioned vs raw cv. 11591 guayule on Avondale soil.

	Emergence/Stand[1]																
	Conditioned--Vermiculite				Conditioned--Soil				Raw--Vermiculite				Raw--Soil				
	Max.	0.95	Day 31		Max.	0.95	Day 31		Max.	0.95	Day 31		Max.	0.95	Day 31		
Depth	Stand	Max.	Stand	Loss	Stand	Max.	Stand	Loss	Stand	Max.	Stand	Loss	Stand	Max.	Stand	Loss	Ratio[2]
	%	Days	%	%	%	Days	%	%	%	Days	%	%	%	Days	%	%	
5	52.6	4.7	32.3	38.6	43.1	5.7	23.6	45.2	38.3	8.4	24.8	35.3	34.8	6.7	16.8	51.8	1.5
10	62.2	6.0	46.8	24.8	30.5	4.5	10.1	66.9	33.9	8.8	18.7	44.8	18.7	6.7	11.7	37.5	3.3
20	43.4	6.2	20.8	52.1	17.2	4.7	11.4	33.7	26.5	12.1	13.5	48.9	9.3	7.7	6.3	32.0	4.7
30	35.8	6.7	19.9	44.4	6.4	6.1	2.7	57.8	12.1	12.3	4.8	60.3	1.8	6.0	0.2	87.5	19.9
Ratio[3]	1.7		2.4		6.7		8.7		3.2		5.2		19.3		84.0		
Diff.[4]	26.4		26.9		36.4		20.9		26.2		20.0		33.0		16.6		

1/ Adjusted by dividing actual percent stands by laboratory determined germination (0.74 and 0.62 for conditioned and raw seed, respectively).
2/ Ratio of highest and lowest maximum emergence at each depth.
3/ Ratio of highest and lowest emergence for each seed-cover treatment.
4/ Difference between highest and lowest emergence for each seed-cover treatment.

Table 3a. Effects of four irrigation schedules on emergence and establistment of direct seeded guayule (Exp. 4; planted Sep. 17, 1987 on Avondale soil).

		Emergence[1/]		Stand	
Irrigation	Depth	Maximum	95% Max.	29-Day	Loss[2/]
	mm	---%---	Day	---------%---------	
I	5	50.3 ± 8.5	5	25.5 ± 8.0	49.4
	10	58.8 ± 10.8	5	31.5 ± 12.1	46.4
	15	57.3 ± 8.8	6	25.0 ± 7.1	56.4
	20	60.3 ± 10.8	8	23.0 ± 5.8	61.8
II	5	29.1 ± 11.4	5	16.7 ± 9.1	42.7
	10	52.7 ± 15.2	7	34.5 ± 8.0	34.5
	15	64.4 ± 8.2	7	45.2 ± 19.4	29.9
	20	57.3 ± 4.0	8	23.9 ± 3.3	58.2
III	5	22.0 ± 11.1	8	15.9 ± 10.6	27.6
	10	39.4 ± 8.3	8	26.1 ± 7.9	33.8
	15	56.8 ± 21.1	8	38.6 ± 14.1	32.0
	20	47.7 ± 6.7	8	23.9 ± 10.3	49.8
IV	5	25.0 ± 7.4	8	10.6 ± 7.0	57.6
	10	36.4 ± 7.6	8	19.4 ± 6.5	50.0
	15	46.7 ± 12.0	8	31.8 ± 7.1	31.8
	20	34.8 ± 9.2	9	12.1 ± 3.3	65.2

1/ Stand counts adjusted for laboratory germination (66%).

2/ Stand loss relative to maximum emergence.

Table 3b. Effects of four irrigation schedules on emergence and establistment of direct seeded guayule (Exp. 4; planted Sep. 17, 1987 on sand soil).

		Emergence[1]		Stand	
Irrigation	Depth	Maximum	95% Max.	29-Day	Loss[2]
	mm	---%---	Day	---------%---------	
I	5	20.5 ± 4.7	8	17.4 ± 3.8	14.8
	10	60.3 ± 13.5	7	50.0 ± 13.5	17.1
	15	63.3 ± 13.9	7	57.6 ± 12.4	9.1
	20	39.7 ± 17.0	10	31.1 ± 11.1	21.8
II	5	10.9 ± 1.52	11	10.3 ± 2.6	5.6
	10	31.8 ± 15.8	8	28.8 ± 13.9	9.5
	15	45.2 ± 2.6		39.4 ± 7.1	12.8
	20	38.6 ± 7.7	8	31.8 ± 9.2	17.6
III	5	12.9 ± 6.7	10	11.4 ± 5.9	11.8
	10	20.5 ± 11.1	9	15.5 ± 11.4	24.4
	15	49.7 ± 19.8	8	36.1 ± 30.2	27.4
	20	43.9 ± 4.4	9	30.0 ± 18.6	31.7
IV	5	3.0 ± 2.4	14	1.8 ± 1.5	40.0
	10	6.4 ± 10.0	4	4.8 ± 8.9	23.8
	15	22.4 ± 7.4	5	15.5 ± 11.8	31.1
	20	27.3 ± 10.8	8	16.4 ± 6.8	40.0

1/ Stand counts adjusted for laboratory germination (66%).

2/ Stand loss relative to maximum emergence.

Table 4a. Effects of four irrigation schedules on emergence and establistment of direct seeded guayule (Exp. 5; planted Oct. 21, 1987 on Avondale soil).

Irrigation	Depth	Emergence[1/] Maximum	Emergence[1/] 95% Max.	Stand 30-Day	Stand Loss[2/]
	mm	---%---	Day	---------%---------	
I	5	59.8 ± 4.4	4	46.2 ± 6.2	22.8
	10	70.9 ± 7.0	5	66.2 ± 7.9	6.6
	15	55.3 ± 14.5	5	41.7 ± 12.0	24.7
	20	41.7 ± 15.2	7	31.5 ± 15.9	24.4
II	5	77.3 ± 8.2	5	67.9 ± 7.3	12.2
	10	73.5 ± 9.4	5	65.9 ± 13.3	10.3
	15	75.5 ± 7.7	6	61.8 ± 7.7	18.1
	20	53.0 ± 12.7	7	44.2 ± 12.6	16.6
III	5	50.3 ± 12.0	5	42.4 ± 8.6	15.7
	10	66.4 ± 8.6	5	59.8 ± 9.7	9.8
	15	68.5 ± 3.2	5	67.0 ± 4.5	2.2
	20	62.9 ± 12.0	8	54.2 ± 15.2	13.7
IV	5	62.1 ± 18.5	4	53.8 ± 18.0	13.4
	10	58.3 ± 16.4	6	59.1 ± 15.2	(1.3)
	15	60.3 ± 14.1	6	52.7 ± 8.0	12.6
	20	48.2 ± 13.3	7	37.6 ± 18.2	22.0

1/ Stand counts adjusted for laboratory germination (66%).

2/ Stand loss relative to maximum emergence.

Table 4b. Effects of four irrigation schedules on emergence and establistment of direct seeded guayule (Exp. 5; planted Oct. 21, 1987 on sand soil).

		Emergence[1/]		Stand	
Irrigation	Depth	Maximum	95% Max.	30-Day	Loss[2/]
	mm	---%---	Day	---------%---------	
I	5	65.2 ± 4.8	5	47.3 ± 12.6	27.4
	10	89.4 ± 11.1	5	76.5 ± 10.4	14.4
	15	75.5 ± 15.0	6	65.9 ± 18.3	12.7
	20	64.4 ± 15.0	8	60.3 ± 23.9	6.4
II	5	59.8 ± 15.2	5	36.4 ± 15.8	39.2
	10	74.5 ± 10.8	6	57.6 ± 9.8	22.8
	15	77.6 ± 6.2	7	60.6 ± 18.9	21.9
	20	63.3 ± 6.5	8	57.9 ± 22.6	8.6
III	5	23.0 ± 5.6	5	20.9 ± 6.5	9.2
	10	61.8 ± 14.4	7	58.3 ± 16.2	5.6
	15	78.0 ± 9.8	7	70.5 ± 7.7	9.7
	20	56.4 ± 8.3	8	50.8 ± 8.5	9.9
IV	5	24.2 ± 6.2	10	23.0 ± 7.1	5.0
	10	54.5 ± 22.1	7	30.6 ± 6.4	43.9
	15	62.1 ± 10.2	7	43.6 ± 21.1	29.8
	20	57.9 ± 7.0	8	47.7 ± 22.0	17.5

1/ Stand counts adjusted for laboratory germination (66%).

2/ Stand loss relative to maximum emergence.

SEEDLING ESTABLISHMENT

SEED FACTORS

INHERITANCE	ENVIRONMENT	ENHANCEMENT
Crop choise	Sun	Size selection
Selection	Rain	Density selection
Breeding	Soil	Purity selection
Bio-engineering	Wind	Storage
	Pests	Dormancy
	Competition	Conditioning
		Pregermination
		Pelleting
		Additives

SITE/SEEDING FACTORS

SITE SELECTION & PREPARATION	SEEDING
Climate	Rate
Soil selection	Mode
Soil enhancement	Depth
Tillage	Precision
Wind breaks	Row covers
Nurse crops	Soil additives
Fallow	Timimg
Drainage	
Preirrigation	
Salt leaching	
Preemergence pesticides	

POST-SEEDING FACTORS

GERMINATION	EMERGENCE	ESTABLISHMENT
Water	Water	Water/irrigation
Salt	Salt	Fertilization
Temperature	Temperature	Temperature
Pests/diseases	Pests/diseases	Shade
Light	Soil density	Pests/diseases
Seed placement	Seed placement	Wind
Seed vigor	Seed vigor	Physiologic factors

Fig. 1. Direct seeding factors affecting seedling establishment.

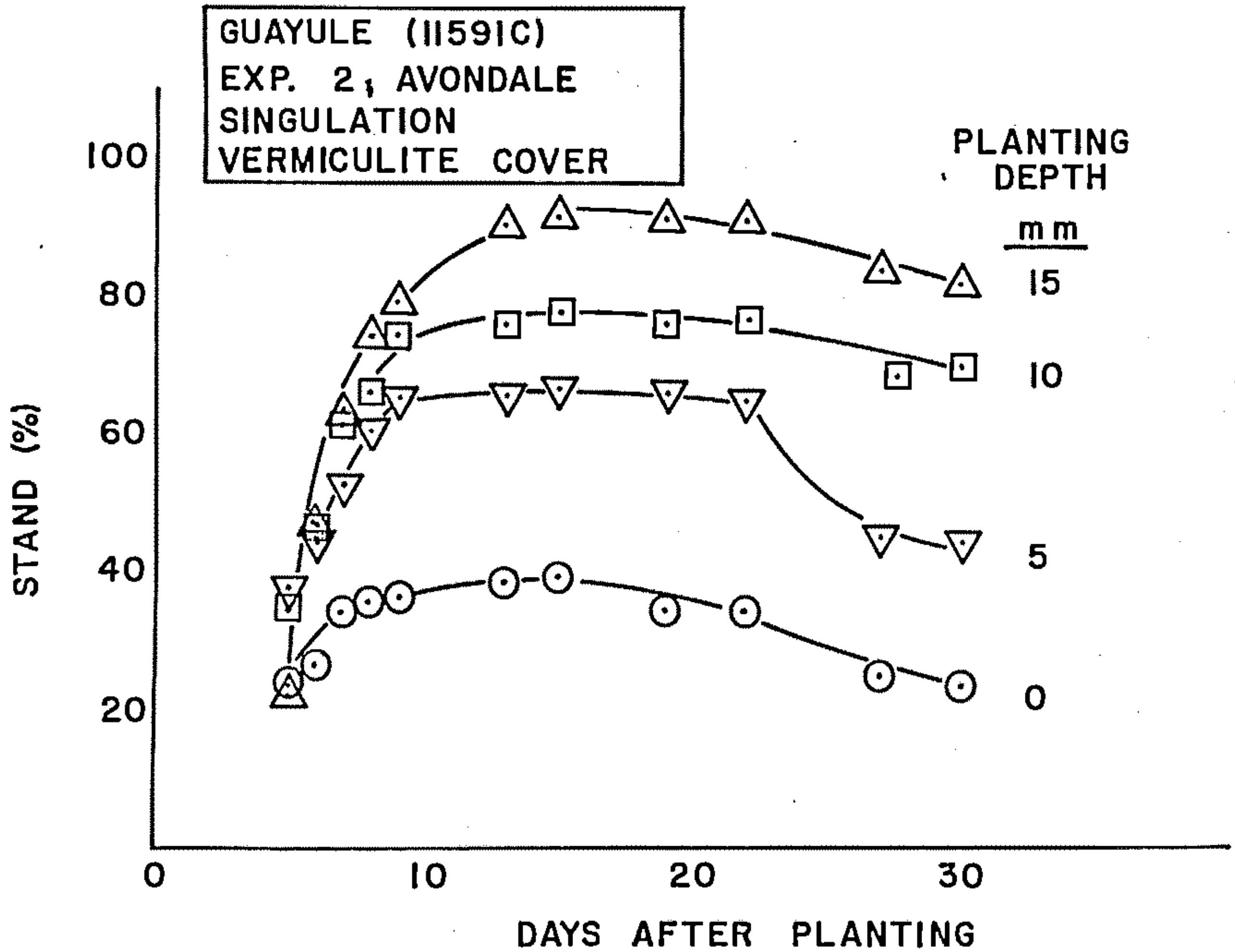

Fig. 2. Emergence/establishment of conditioned guayule at different planting depths.

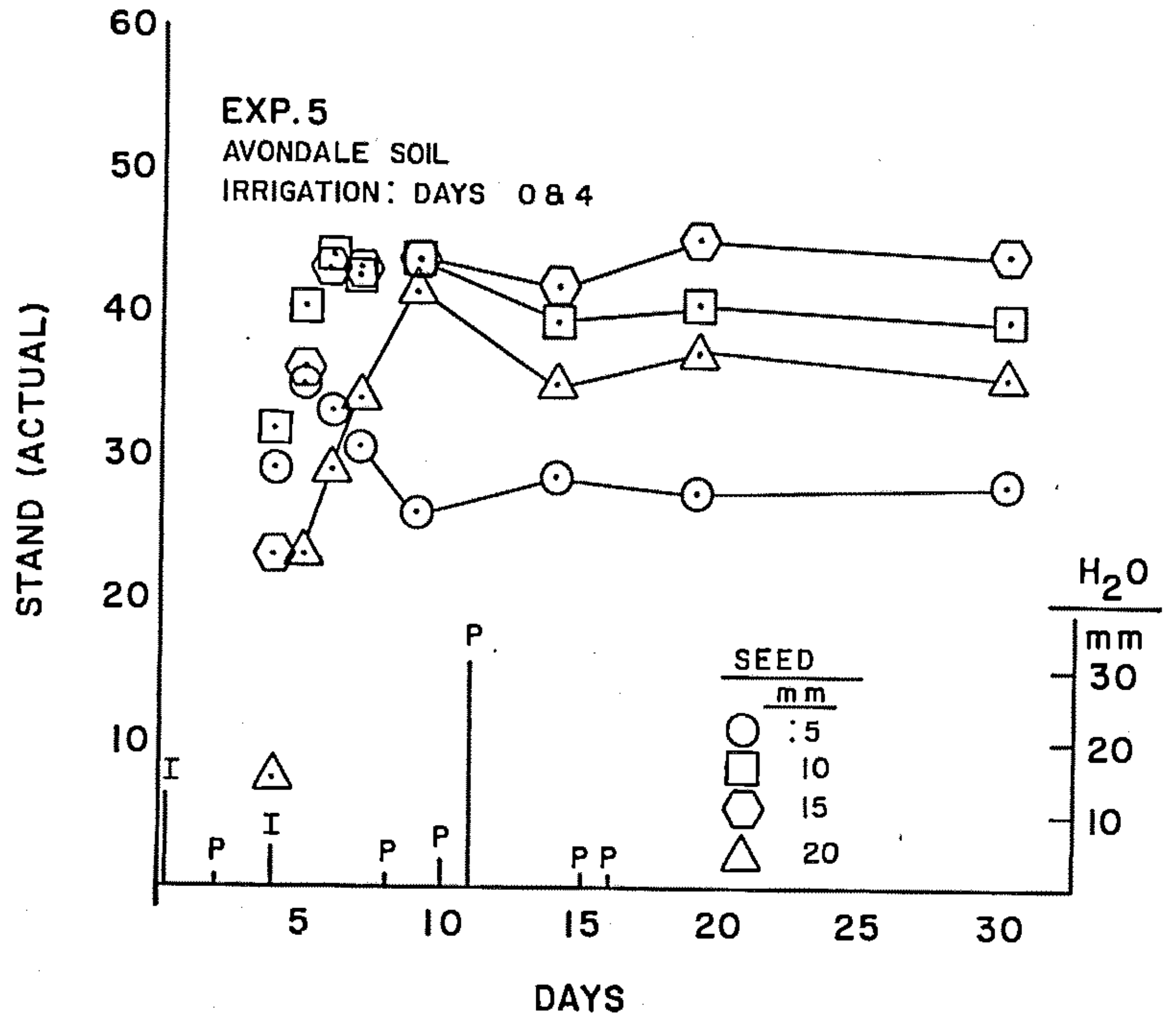

Fig. 3. Emergence/establishment of conditioned guayule at different planting depths for initial and day 4 irrigation regime.

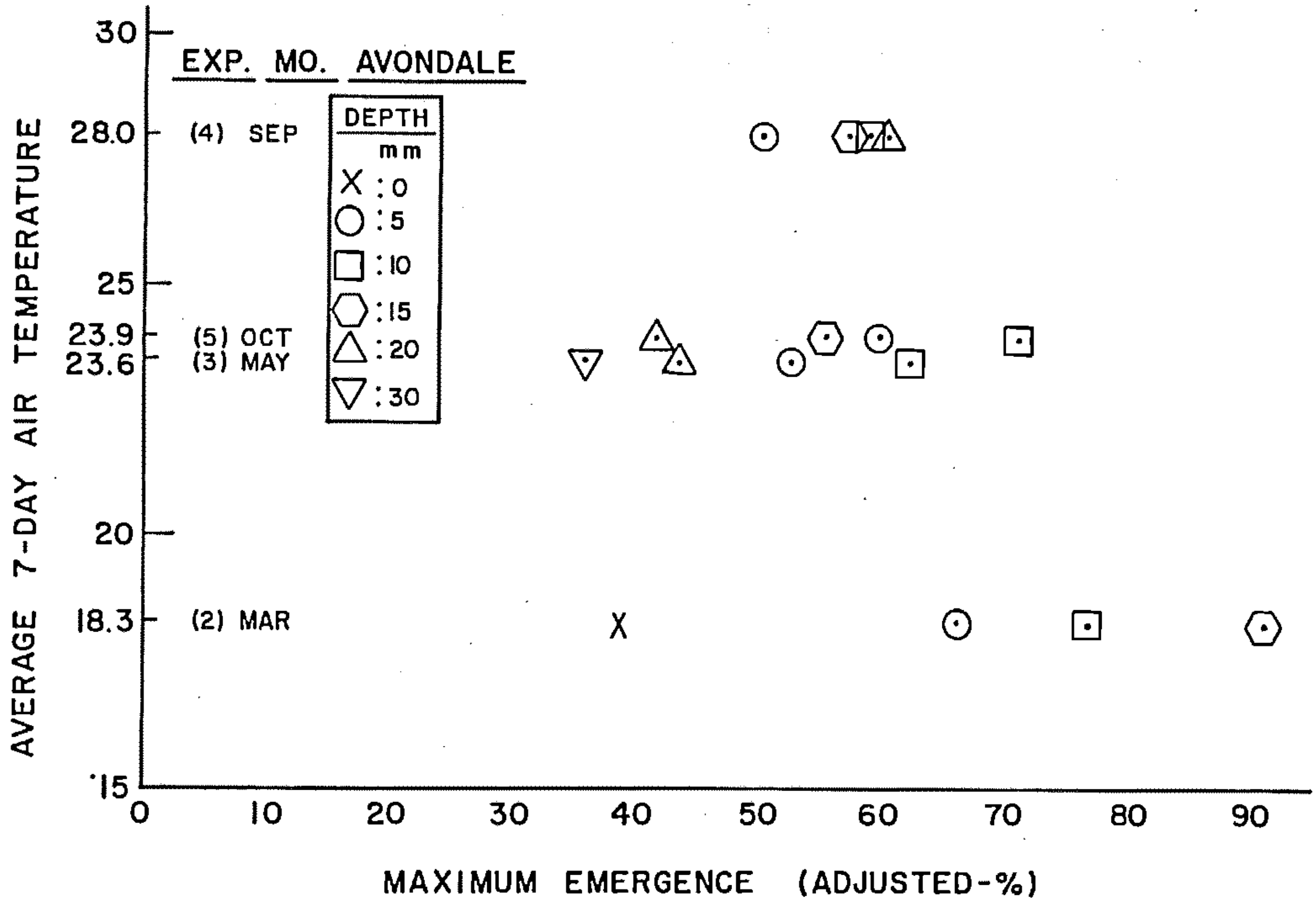

Fig. 4a. Maximum emergence of vermiculite-covered conditioned guayule from different planting depths on sand soil as related to average air temperature during first seven days following planting.

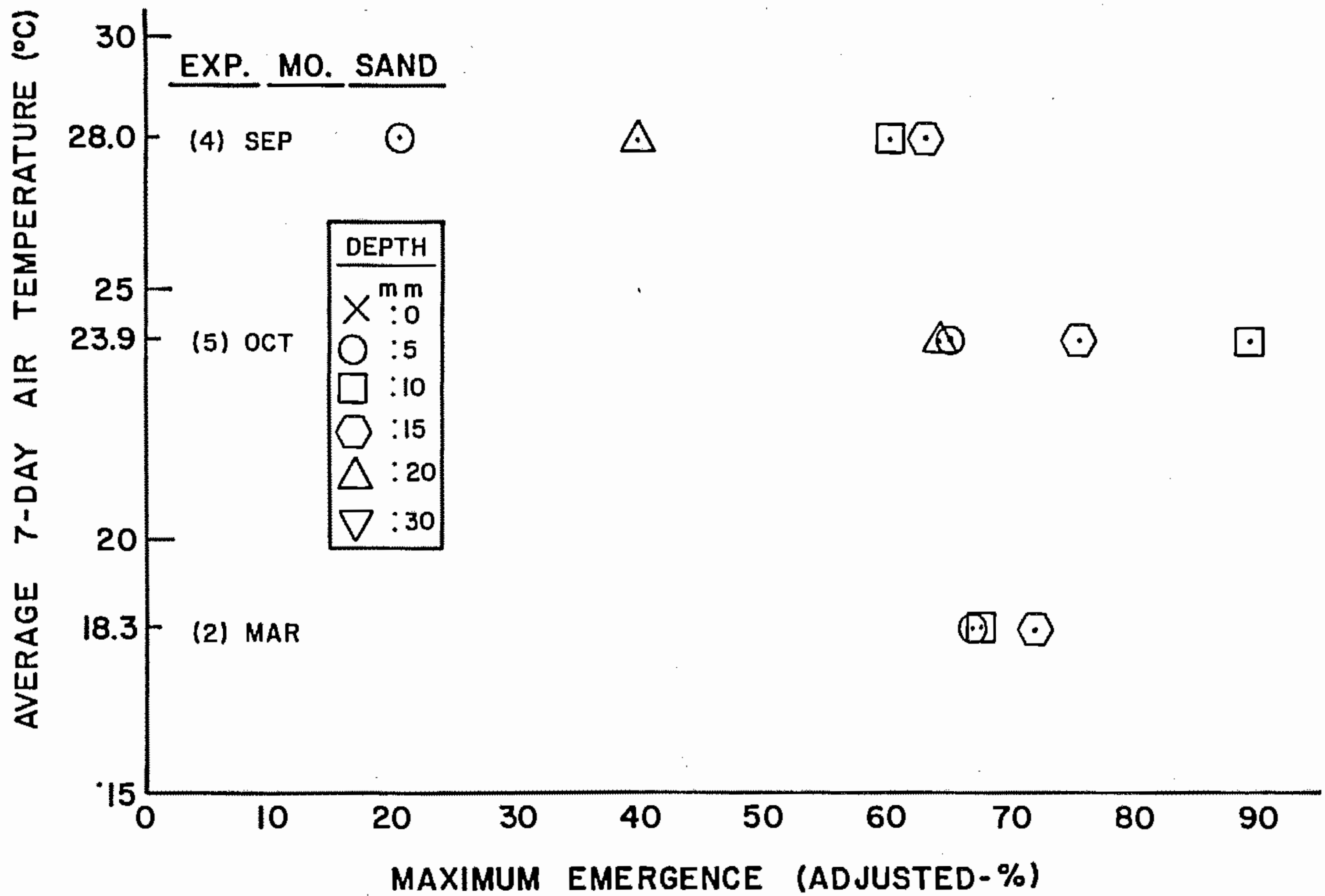

Fig. 4b. Maximum emergence of vermiculite-covered conditioned guayule from different planting depths on Avondale soil as related to average air temperature during first seven days following planting.

TITLE: CULTURAL MANAGEMENT OF LESQUERELLA

SPC: 1.3.03.1.d 80% CRIS WORK UNIT: 5344-13230-001
2.3.04.1.n 20%

INTRODUCTION

The lesquerella plant biosynthesizes hydroxy fatty acids similar to castor oil, which is classified as a strategic material and an essential chemical feedstock for the production of lubricants, plastics, protective coatings, surfactants, and pharmaceuticals. Castor oil is a completely imported item of considerable industrial importance. Economic analyses indicate that the potential crop value justifies research and development of lesquerella as a new crop for the arid areas (Thompson, 1988). Lesquerella is considered a winter crop and may replace other small grain winter crops of the southwest. When used as a winter crop, its water use would be expected to be less than those grown in the hotter periods of the year. At present, we have limited information on the cultural management of this crop. The objective of this study is to determine the water requirement of lesquerella and to begin to understand the cultural management of the crop.

PROCEDURE

The seed source was from a half-sib family bulk population of *Lesquerella fendleri*, which came from progenies of single plant selections. Seeds were planted with a Stanhay belt seeder with approximately 80 seeds per foot using 12-inch rows. The experiment was set up in an 80 X 600-feet, level basin plot located at the Maricopa Agricultural Research Center on a Casa Grande sandy loam soil. Planting was initially made on October 17, 1986, but plant establishment was poor because of soil crusting problems. Replanting was made on December 2, 1986. This later planting was expected to affect cultural management and yield, but a comparison of irrigation treatments was still possible. To improve seed emergence and establishment, sprinkler irrigation was used.

A completely randomized block design with four irrigation levels and four replications was used. Each plot was 40 x 75-feet and surrounded by border dikes. A neutron excess tube was installed in the center of each plot to a depth of 6-foot (180 cm). Weekly measurements of water content was made with the neutron equipment which was field calibrated at the site. Pre- and post-irrigation soil water measurements were also made as the schedule demanded. The water use characteristic of lesquerella was determined by monitoring soil water depletions.

The four irrigation treatments were planned with the following application rates:

A. Two irrigations with approximately 90 to 95% available soil water depletion at the 0-50 cm depth.

B. Three irrigations with approximately 80 to 85% available soil water depletion.

C. Four irrigations with approximately 70 to 75% available soil water depletion.

D. Five irrigations with approximately 60 to 65 % available soil water depletion.

The pre-planned irrigation levels had to be modified because of the late planting date, weather conditions, and unknowns in the phenological development of the lesquerella crop.

Ammonium phosphate (16:20) was applied at the rate of 100 lb/A as the preplant fertilizer. No herbicide was used and weeds were controlled by manual removal.

Seeds were hand-harvested on July 1, 1987.

RESULTS AND DISCUSSION

Because of the late planting date, the irrigation scheme had to be modified from the initial criteria set up for the experiment. Thus, only 1, 2, 4 and 5 irrigations were made for Treatments A, B, C, and D, respectively, instead of 2, 3, 4 and 5 as initially planned (See Table 1 for actual irrigation dates). The second irrigation for Treatments A and B was not applied in order to prepare the plants for harvesting. Possibly, an irrigation should have been applied in early to mid-April for these treatments to achieve the 2 and 3 irrigation levels.

The moisture distribution curve and the changes in water content with time are illustrated in Figure 5 for treatment A. Root activity and water adsorption was occurring primarily at the 0 to 130 (not plotted) cm depth with practically none at the 180 cm.

The consumptive water use curves for the four treatments (Figs. 1 to 4) indicate that minimal water use occurred over the January through April period when the evapotranspirational demands are the lowest. Approximately 90% of the water used for evapotranspiration was derived from the 0 to 90 cm soil depth. Lesquerella is an indeterminate flowering plant and flowering started in late February and continued until soon after the irrigation ended. Most of the water use occurred over the late April through the early June period. Irrigation was terminated in early June to prepare the plant and soil for seed harvesting.

The yield vs. water use data are presented in Table 2. Maximum yield of 569 kg/ha was attained at the 5 irrigation level. The yield, however, is much below the 2,500 kg/ha value needed as a break-even cost of production reported by Thompson (1988). A yield of at least 1,000 kg/ha could have been achieved if plant establishment could have been made in October. The extra irrigation applied in Treatment D vs. C had a great effect on yield even though the water use increase was only 5 mm.

Apparently, like other crops, a critical time of non-stress condition is present for seed production in lesquerella, which occurs in this instance during the late May to early June period.

Seed size was similar for all treatments. The single weights are lower than those reported by Thompson (1988) for greenhouse grown plants which were later transplanted to the field.

Water use of 425 mm (16.7 in.) for lesquerella is below other small grain crops grown in this area such as barley (635 mm, 25 in.) and wheat (655 mm, 25.8 in.); castor bean for castor oil, also grown here in the past over the April to November season requires 1128 mm (44.4 in.) under normal production (Erie, et al., 1981).

SUMMARY

Establishment problem was encountered in the first large-scale planting of lesquerella. This was solved by using sprinkler irrigation. Water use by lesquerella is in the order of 420 mm over the December to June winter growing season, which is less than that for winter small grain crops such as barley and wheat. Seed yield was low and could be attributed to the later than normal planting date used. Little water was used over the December to March interval, with the maximum occurring in May. Additional field trials are needed to include experiments to study the interaction of water, fertility, population, and germplasm for optimum management of the crop.

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PERSONNEL

D. A. Dierig, A. E. Thompson, F. S. Nakayama, and W. L. Alexander

Table 1. Irrigation application dates

Treatment*	Date
A	12 May 1987
B	05 May 1987 26 May 1987
C	29 Jan 1987 23 Apr 1987 12 May 1987 26 May 1987
D	29 Jan 1987 23 Apr 1987 12 May 1987 19 May 1987 02 Jun 1987

* 100 mm (4-in.) of water application per irrigation; 56.8 mm rainfall over the experimental period.

Table 2. Lesquerella seed yield and water use relations

Treatment	No. Irrig.	Seed yield (kg/ha)	Seed weight (g/1000)	Water-use* (mm)
A	1	141	0.484	280
B	2	214	.509	340
C	4	437	.484	420
D	5	569	.525	425

* Computed for the 0-190 cm depth.

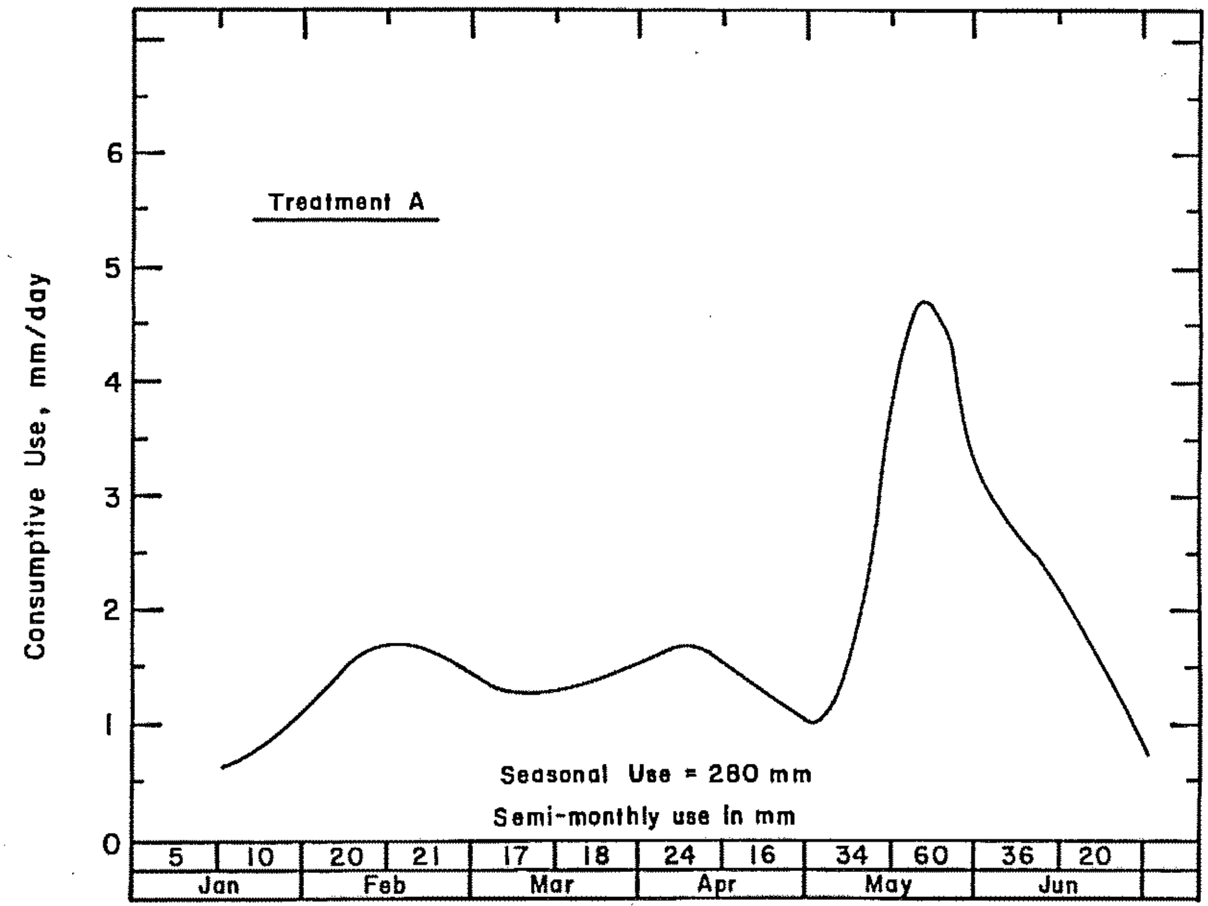

Fig. 1. Seasonal water use for lesquerella, Treatment A (1 irrigation), at Maricopa, Arizona, 1986-1987.

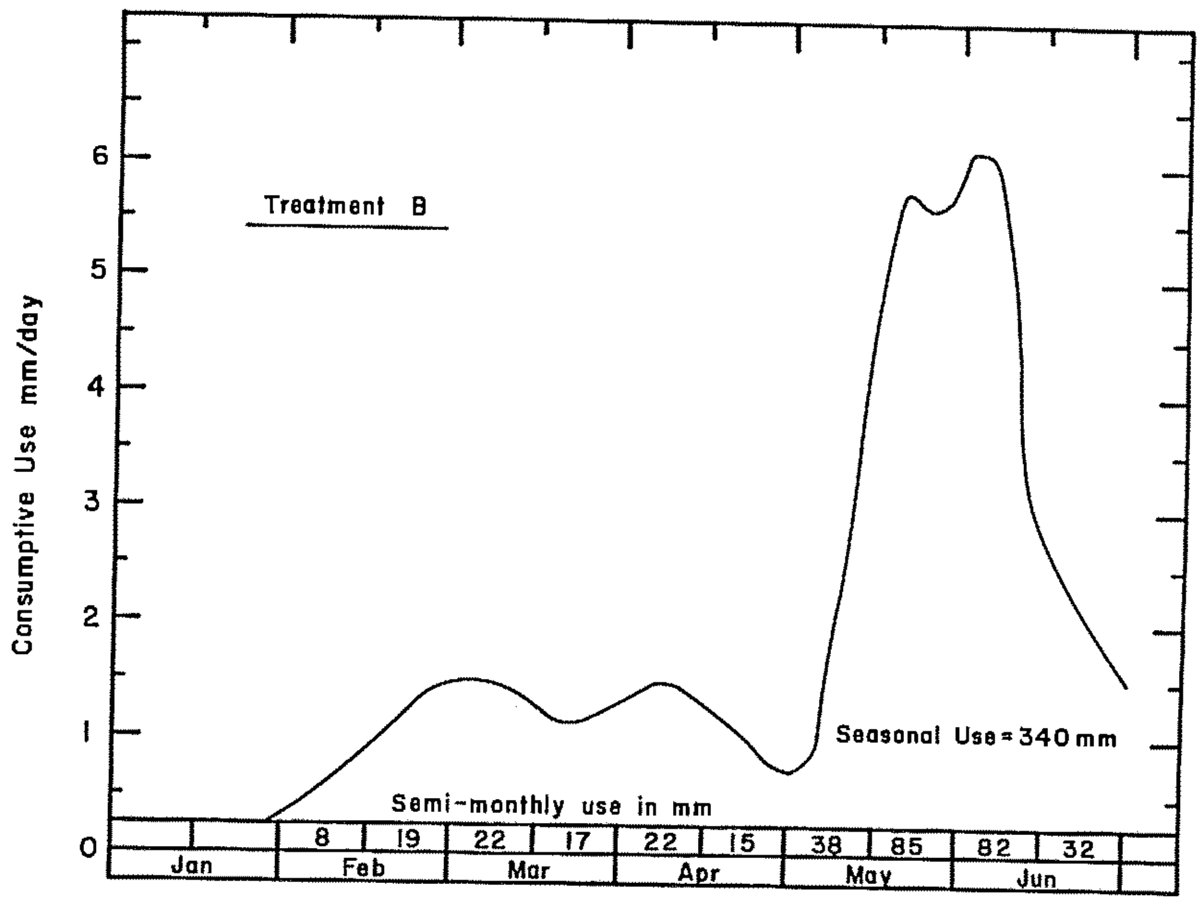

Fig. 2. Seasonal water use for lesquerella, Treatment B (2 irrigations), at Maricopa, Arizona, 1986-1987.

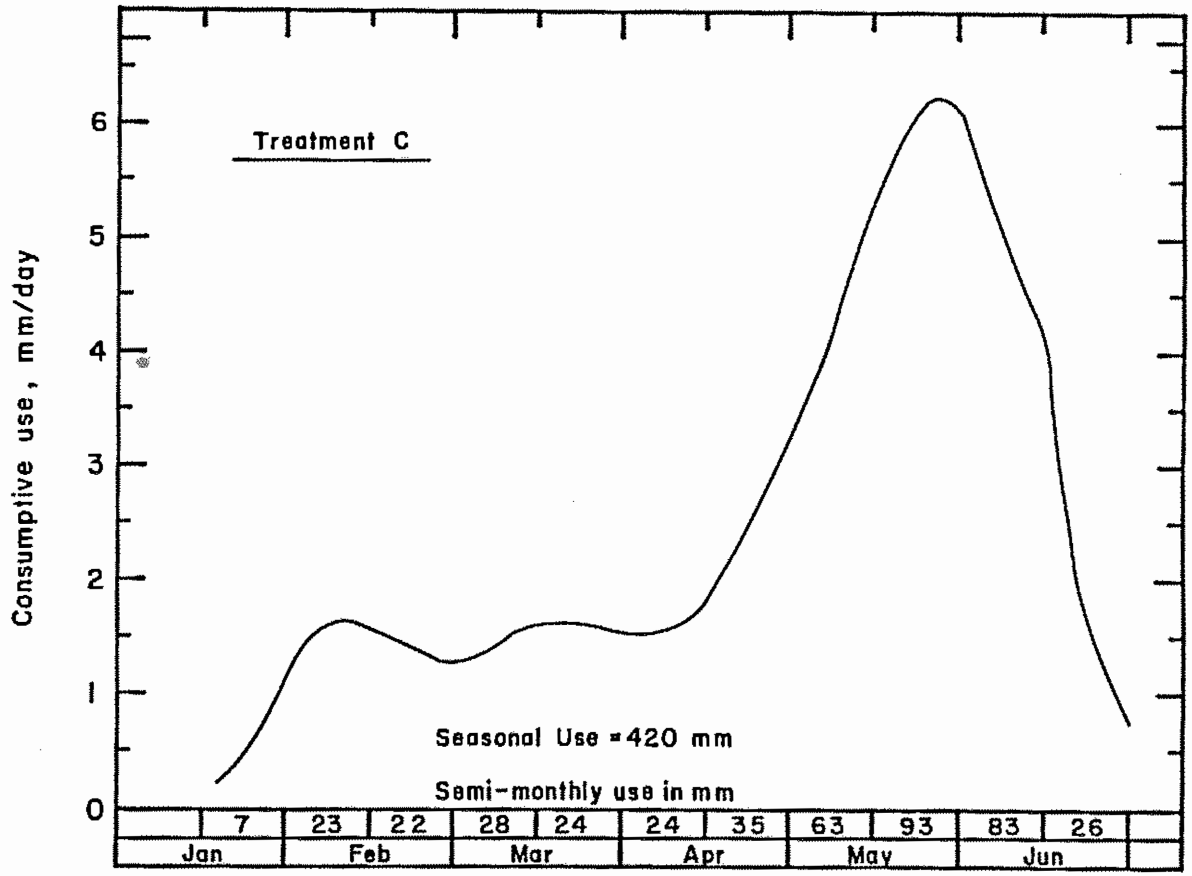

Fig. 3. Seasonal water use for lesquerella, Treatment C (3 irrigations), at Maricopa, Arizona, 1986-1987.

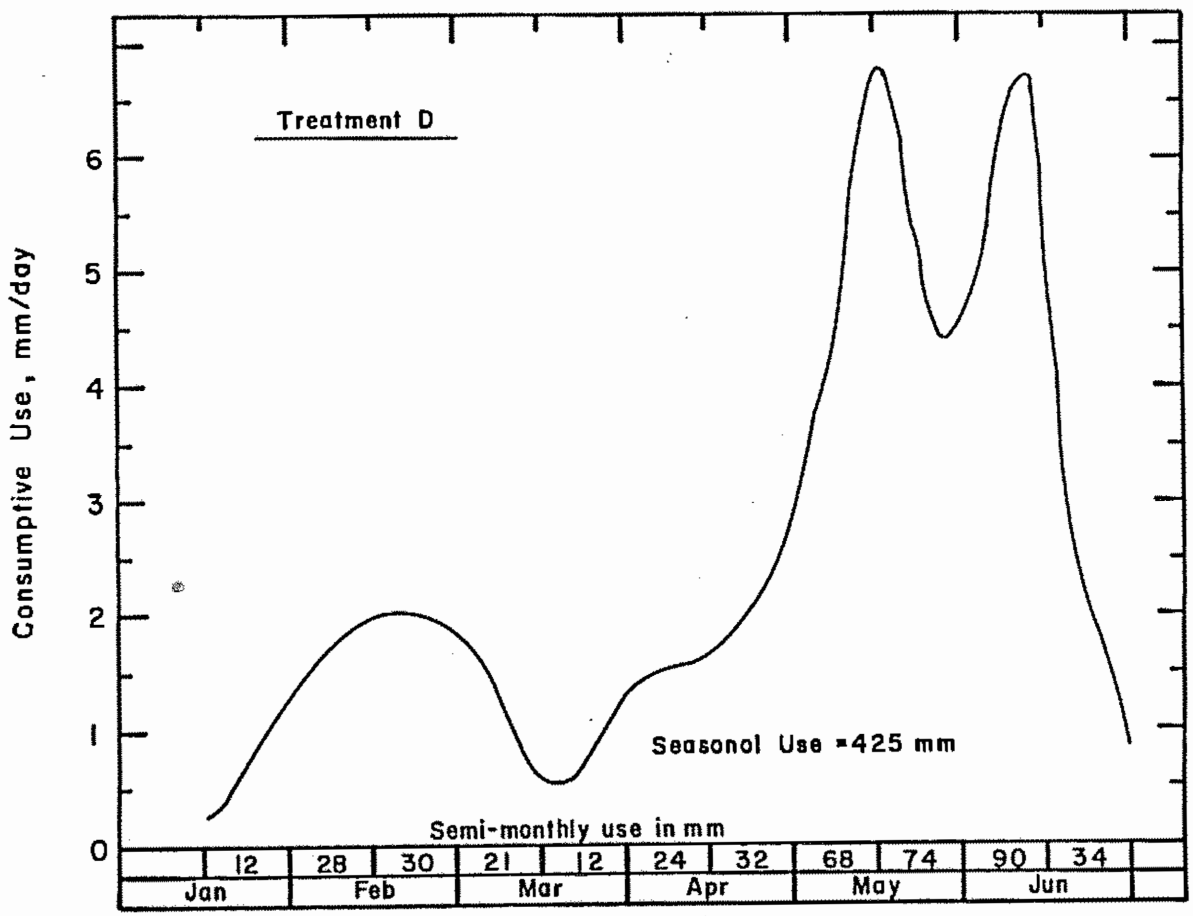

Fig. 4. Seasonal water use for lesquerella, Treatment D (4 irrigations), at Maricopa, Arizona, 1986-1987.

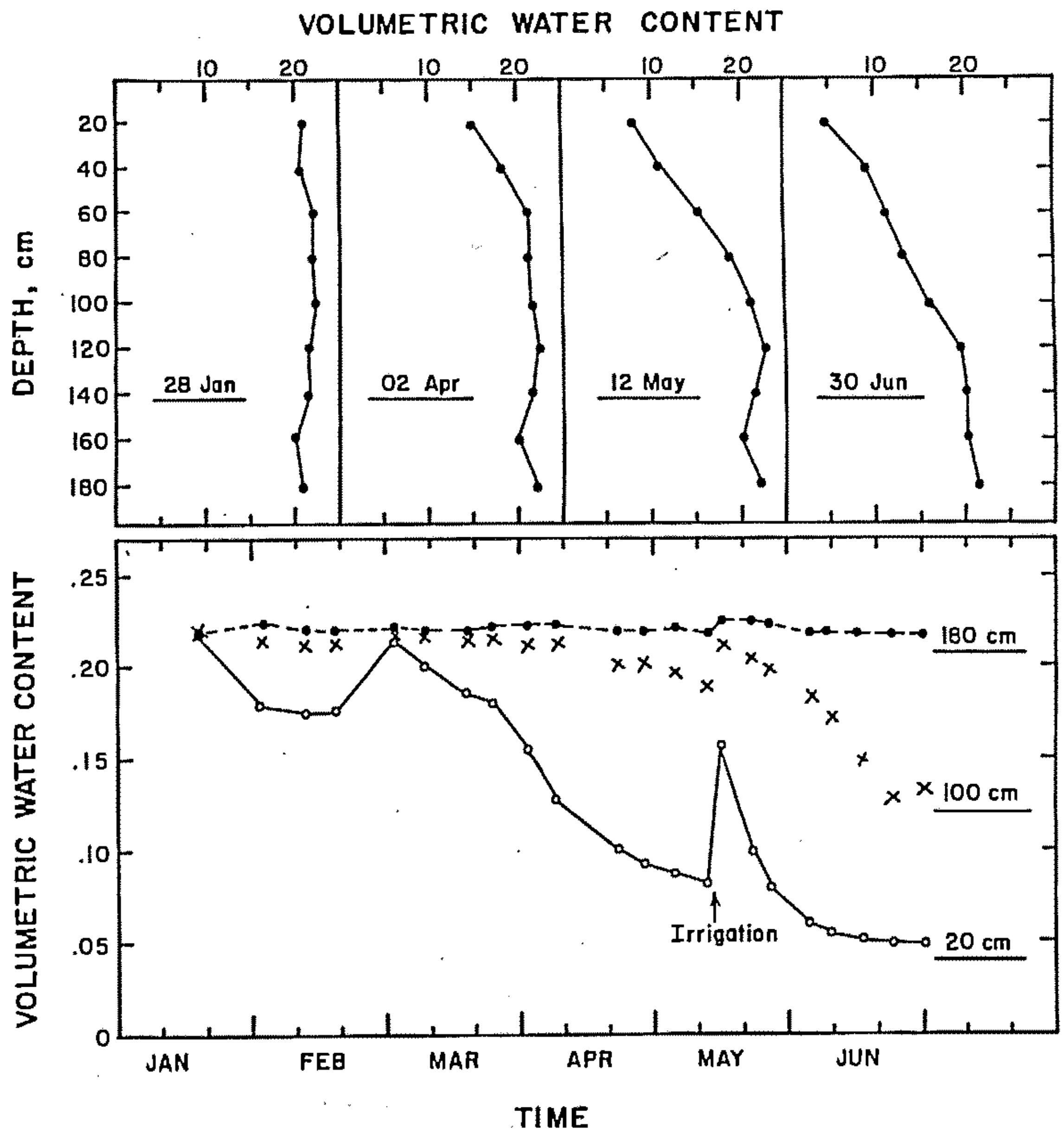

Fig. 5. Soil moisture distribution and water content for a given depth as a function of time. (Treatment A).

TITLE: DCPTA EFFECT ON RUBBER AND GROWTH OF GUAYULE AND SEVERAL OTHER PARTHENIUM SPECIES

SPC: 2.3.04.1.p CRIS WORK UNIT: 5344-13230-001

INTRODUCTION

In recent years, the United States has been importing its entire supply of natural rubber, approximately 800,000 metric tons annually, at a cost of about $870 million (Green, 1986). Guayule (Parthenium argentatum Gray) is a drought-tolerant, rubber-producing shrub native to north central Mexico and southwestern Texas. Research and development efforts to commercialize guayule rubber production in the United States are the result of this country's dependence on foreign sources of Hevea brasiliensis rubber to meet its natural rubber requirements. Besides helping to relieve the nation's trade imbalance and providing a reliable supply of this critical material independent of the vagaries of the international market, the domestic production of guayule rubber will provide a sorely needed alternative crop for farmers in the desert southwest.

Although plant breeders are working to increase the rubber content of guayule plants, the 8 to 10% rubber currently found in the best genetic material is inadequate to justify commercial production at current rubber prices (Wright, 1985).

Other methods of improving guayule rubber yields have been studied, including bioregulation of the percentage of rubber in the plant. The chemical bioregulator DCPTA [2-(diethylamin)ethyl 3,5-diisopropyl phenyl ether], in particular, has been observed to increase the rubber yield of guayule (Yokoyama et al., 1977; Hayman et al., 1983; Yokoyama et al., 1983; Hayman et al., 1987). DCPTA reportedly stimulates the activity of enzymes involved in rubber synthesis (Benedict et al., 1983; Benedict et al., 1985), but its effectiveness is thought to be limited by the capacity of the parenchyma cells in the stem to store the rubber thus synthesized (Yokoyama et al., 1983).

Another approach to increasing rubber yields has been through hybridization of guayule with other Parthenium species which have much higher biomass yields, though lower rubber content, than guayule (Rollins, 1946; Tysdal, 1950; Youngner et al., 1986; Naqvi et al., 1987). F_1 hybrids resulting from these crosses generally have biomass and rubber content intermediate to the parents (Naqvi et al., 1987). It is postulated that the stem parenchyma cells of these hybrids and their non-guayule parents may have a capacity to store more rubber than they naturally produce, in which case, DCPTA may be able to stimulate rubber synthesis and consequently increase rubber content.

The present experiment was designed to test the effectiveness of DCPTA in promoting increased rubber yield of guayule, several other Parthenium species, and a hybrid resulting from the mating of guayule and P. tomentosum. In addition, we wished to compare rubber and biomass yields of the aforementioned genotypes when grown in the Sonoran Desert of Arizona.

MATERIALS AND METHODS

Seedlings of Parthenium schottii, P. tomentosum, P. incanum, P. argentatum (cvs. 11591 and 11634) and a putative hybrid of P. tomentosum x P. argentatum (cv. Arizona 101) were started from seed planted on 13 January 1986 and grown in a greenhouse in conditions described in detail by Allen, et al. (1987). The 70-day-old seedlings were transplanted by hand into field plots at the University of Arizona Maricopa Agricultural Center, Maricopa, Arizona, on 27 March 1986, where the soil type is a Mohall sandy loam (fine-loamy, mixed, hyperthermic, Typic haplargid) (USDA, 1975).

The plants were furrow-irrigated immediately following transplantation into the field plots, at approximately two-week intervals thereafter through October 1986, then at approximately monthly intervals through February 1987.

The field plots were arranged in a split-plot design, with bioregulator treatments as main plots and genotypes as subplots. The treatments were replicated three times. Each individual plot consisted of a total of 18 plants in three 4.0 m rows on raised beds. The beds were spaced 1 m apart and plants within each bed were spaced 0.7 m apart.

The bioregulator DCPTA was applied to the plots a total of six times, three in the spring (May 28 and June 4 and 11) and three in the fall (September 16, 23, and 30) of 1986, when the plants were observed to be vigorously growing. DCPTA was applied in two concentrations, 300 and 600 mg L^{-1}, based on previous studies at this laboratory (unpublished data) and another (Paterson-Jones, 1985) that indicated that higher concentrations damaged leaf tissue and reduced growth. Each treatment solution, as well as a distilled-water control, contained 0.01% Tween 80 as a surfactant (Aldrich Chemical Co., Inc., Milwaukee, WI). Treatment solutions were applied only on calm, clear days between 0800 and 0900 hr. local time, using a 10 L hand-held sprayer, until the solutions completely covered and were dripping from the adaxial leaf surfaces. Approximately 45 ml of solution were applied to each plant on each treatment date.

Five plants, including most of the roots, from the middle row of each plot were harvested and their fresh weights measured on February 4, 1987. Rubber and resin contents of four of these plants from each plot were measured according to the procedure of Black et al. (1983). The other plant from each plot was oven-dried to constant weight, and its moisture content calculated and used to estimate dry weight of the four other plants harvested from the same plot. This procedure was necessary because oven-drying of guayule can lead to rubber degradation.

The amount of rubber per plant was calculated from dry weight and percent rubber data. An analysis of variance (ANOVA) was performed on the data for each of the aforementioned parameters. Least significant difference treatment mean separations were conducted for those factors found to be significant at $P < 0.01$ with the ANOVA.

RESULTS AND DISCUSSION

As can be clearly seen from the ANOVA summary in Table 1, the DCPTA treatments did not significantly affect biomass, rubber content, resin content, or rubber yield per plant. Although other studies have shown that DCPTA can, under certain circumstances, increase rubber yield, ours is not the first study in which guayule did not respond to DCPTA treatment. Bucks et al. (1985) found no significant effect of DCPTA on rubber yields or rubber content of field-grown guayule and Paterson-Jones (1985) reported that DCPTA was detrimental to guayule growth and ineffective at increasing rubber content.

Furthermore, even in those studies where DCPTA effectively increased rubber yields, the yield components affected by DCPTA differed. In some studies, DCPTA has been reported to increase the percentage of rubber in the plant (Yokoyama et al., 1977); in other studies, however, DCPTA increased rubber yield by increasing plant biomass, leaving percentage rubber content unchanged (Hayman et al., 1983).

A lack of consistent and repeatable results from bioregulator studies is not unusual. Bhalla (1981) described results from experiments with the growth regulator triacontanol as "consistently inconsistent." Another growth regulator, mepiquat chloride, produced inconsistent results when applied to cotton (Briggs, 1981); the effects were highly sensitive to environmental conditions. A similar inconsistency of effect appears to be true for the bioregulator DCPTA and may limit its use for commercial applications unless specific environmental conditions under which DCPTA applications prove successful can be identified. Unfortunately, environmental conditions in our experiment and the other experiments concerning DCPTA application to guayule cited in this paper were not monitored or reported, making such identification difficult.

Table 1 also shows that there were significant differences among genotypes in plant biomass, percent rubber, and rubber yield per plant. The mean values of these parameters are shown in Table 2. Arizona 101 and *P. tomentosum* produced approximately three times as much biomass as all other genotypes; but the two *P. argentatum* entries had significantly higher percent rubber than the other genotypes. It is interesting to note that the hybrid Arizona 101 had 2.4% rubber, approximately midway between the parental genotypes, *P. argentatum* and *P. tomentosum*. The combination of high biomass and intermediate percent rubber caused Arizona 101 to have significantly higher rubber yield per plant (13.7 g) than all other genotypes. The next highest rubber yield belonged to *P. argentatum*, with an average of 7.6 g rubber per plant, 45% less than Arizona 101. Rubber yields of the other genotypes, *P. tomentosum*, *P. schottii*, and *P. incanum*, were all less than one-tenth that of Arizona

101 due to their low percent rubber content. The favorable performance of Arizona 101 suggests that interspecific hybridization is a valuable breeding tool for increasing guayule rubber yield.

This study resulted in two significant findings. First, the bioregulator DCPTA was found ineffective at increasing rubber yields of guayule or several other *Parthenium* species, either via increased biomass or increased rubber content when the plants were grown in environmental conditions of the Sonoran Desert of Arizona. Second, the interspecific hybrid Arizona 101 produced significantly higher rubber yields per plant than all other genotypes after the first year's growth. This study, therefore, confirms previous reports suggesting the utility of interspecific hybridization as a method for increasing guayule rubber yields.

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PERSONNEL

S. G. Allen and F. S. Nakayama

Table 1. Summary of statistical significance from ANOVA's for plant biomass, percent rubber, and rubber yield per plant.

Source	Degrees of Freedom	Error Mean Square: Plant Biomass(g)	Percent Rubber	Rubber Per Plant(g)
Blocks	2	9,935	.13	.63
DCPTA	2	2,867	.04	.89
Error 1	4	8,864	.13	2.36
Genotype	5	420,300**	40.17**	258.90**
DCPTA X Genotype	10	5,878	.03	3.12
Residual	30	5,400	.12	2.51

** Significant at $P < 0.01$.

Table 2. Effect of DCPTA on plant biomass of several *Parthenium* species.

Parthenium Species	Plant Biomass(g): DCPTA Treatment: Control	300 mg L[1]	600 mg L[1]	Mean
P. schottii	190	139	205	178 a[1]
P. tomentosum	594	654	618	622 b
P. incanum	179	204	197	194 a
P. argentatum cv. 11591	291	127	169	196 a
cv. 11634	193	141	191	175 a
P. tomentosum X *P. argentatum* cv. Arizona 101	578	607	568	584 b

[1] Means followed by same letter are not significantly different at 0.01 level by LSD test.

TITLE: DIRECT SEEDING FOR ECONOMICAL GUAYULE RUBBER PRODUCTION

SPC: 2.3.04.1.n
1.3.03.2.d

CRIS WORK UNIT: 5344-13230-001

INTRODUCTION

Commercial production of guayule (Parthenium argentatum Gray) has been hindered by expensive or inappropriate agronomic practices, particularly the techniques associated with stand establishment. Guayule is presently being established through the transplanting of greenhouse-grown seedlings into the field. The cost of this establishment, including greenhouse and transplanting procedures, was estimated in 1985 to be from $900 to $1200 per ha. The development of direct seeding techniques could reduce this in half. Recent studies with guayule direct seeding indicate acceptable stands can be established through better field management and the control of environmental conditions.

Four years (1983, 1984, 1985 and 1986) of direct seeding studies of guayule in Yuma Arizona and Maricopa Arizona have provided researchers with sufficient data to justify the elimination of nonconditioned guayule seed and the exclusive use of the superior-performing seed conditioned with polyethylene glycol (PEG), gibberellic acid (GA) and light. The direct seeding historic data also points to a need to study the interactions between irrigation water applications, row cover treatments, and cultural practices.

Spring and fall 1987 direct seeding experiment were conducted at the Maricopa Agricultural Center, University of Arizona, Maricopa, Arizona, on a Casa Grande sandy loam soil. The objective of this study was to continue examining the effects of synthetic and natural row shade covers and specific direct seeding methods using conditioned seed only. In addition, a comparison of seedling growth was made between directly-seeded guayule and greenhouse-grown guayule transplanted into the plots adjacent to the spring 1987 direct seeding experiment.

FIELD PROCEDURES

Spring 1987

The field, which was 14 m (twelve beds) wide and 185 m long, was divided into four replications and eight horizontal row cover treatments (A) bare soil, (B) first wheat planting cover crop, (C) second wheat planting cover crop, (D) Agronet coextruded polypropylene/nylon (10% solid shade cover), (E) Reemay spun-bounded polyester (20% solid shade cover), (F) polyshade cloth (40% solid shade cover) (G) polyshade strips (40% shade, 300 mm wide strips) and (H) American straw mat (25 mm thick, solid shade cover), as main plots. The three vertical planting methods were (FI) surface fluid drilling of conditioned, same range as the two highest ranked survival rate treatments, but were unable to establish or maintain acceptable stands of guayule seedlings because of competition for water by wheat plants and extreme environmental conditions.

Average weekly air temperature, relative humidity and solar radiation readings on no cover and on one or both wheat cover crops are presented in Table 1. The data collected can be used to make some general observations over the one month establishment period. The wheat crop covers provided some of the desired conditions for guayule establishment. They reduced the gross solar radiation by an average of 31% over the no cover treatment and the open canopy provided adequate sunlight for normal plant development. The wheat covers also reduced the maximum bare soil temperature levels by 3.3 degrees C and minimum by 1.8 degrees C over the one month period and increased the maximum relative humidity by 40% over the no cover treatment. As can be seen on Table 2 the wheat cover crops provided for average soil temperatures in an acceptable range, but soil water depletion by the actively growing wheat resulted on a deeply crusted seed bed and an inadequate supply of water during critical growth stages (Table 3).

Further studies were conducted on the effects of plant water stress for five selected row cover treatments: no cover, first wheat, Agronet, polyshade cloth and American straw mat. Plant water potential summaries obtained on three selected dates are presented in Table 5. Seedling water potential readings were obtained with thermocouple psychrometers, cotyledon (under surface, 5 mm above ground) and 5 mm air temperatures by individual thermocouple leads and soil surface temperature with an infrared temperature sensor. The readings present the seedling response to the interaction between extreme environmental conditions and the specific row cover treatment.

When averaged over the three reading dates, the first wheat cover exhibited extreme symptoms of water related stress with a seedling water potential 30% lower than that of the no cover treatment, and an elevated cotyledon temperature. The environmental readings indicated an extreme soil moisture depletion in the wheat (5.5% moisture by weight at the 0-30 mm depth) and elevated 5-mm-above-ground and soil surface temperatures (Table 5). The soil surface temperature was moderated because of the wheat canopy shade effect. Of particular interest is the response of seedlings under the Agronet shade cover. These seedlings exhibited the lowest seedling water potential (-12.9 bars) (Table 5), but at the same time, experienced the highest overall 5-mm-above-ground and soil surface temperatures and a high cotyledon-undersurface temperature. Given these extremes, acceptable stands of 7 seedlings per meter were still achieved.

The soil moisture content for the Agronet was low, but in the acceptable range. This indicates that guayule can be established under extreme above ground temperatures, given adequate soil moisture and a shade cover that provides elevated above ground temperatures, traps the eleven counting dates for each row cover treatment indicate the following trends in the 0-30 mm depths. American straw mat maintained the highest percentage soil moisture (Table 3) throughout the experiment with a high survival rate of plants (third highest ranking). This high spring 1987 survival rate is attributed to the fact that, in this instance, the straw mat was laid in direct contact with the seed bed, allowing the seedling the opportunity of growing up through the straw mat. It also eliminated the damp dead airspace created by the fall 1986 20 mm deep corrugated seed bed.

The soil moisture percentage remained about the same between the shade cover and shade strips at the 30-50 mm level, but at the 0-30 mm level the polyshade strips remained much drier, as much as 30% drier in the last month of the experiment. During this time, polyshade strips exhibited a 25% increased survival rate over the polyshade cloth. The remaining two synthetic row covers (Agronet and Reemay) performed well. The Agronet survival rate was slightly higher than the Reemay even though the Agronet soil moisture percent was quite low during the experiment (Table 3). The three driest row cover crops, no cover, first wheat planting and second wheat planting maintained the lowest soil water content, sometimes dropping to four to six percent soil moisture by weight. The average rate of these three treatments was 83% less than the lowest synthetic (Reemay) cover (1.2 vs 7.3 seedlings per meter). The two wheat crops were actively growing during guayule establishment and depleted the moisture available to the guayule seedlings. The extreme die off of seedlings in the no cover plot was caused by intense direct solar and reflected radiation, lack of moisture at critical periods and salt accumulations.

Soluble salt levels were significantly higher in these three driest treatments during the last week of sprinkler irrigation and the first flood irrigation (Fig. 2). The soluble salts for the three treatments went from an average of 1568 mg per l on April 27 to 3902 mg per l on May 8. The average soil moisture content (0-30 mm) for the three went from 7.6 to 5.0% weight per volume between the same two dates. On May 29 the no cover total soluble salt level exceeded 6000 mg per l.

Average weekly soil temperatures on the eight row cover treatments are presented in Table 1. As during the fall 1986, the soil temperatures resulted from the very specific conditions under each individual row cover treatment. In the spring of 1987 the row cover treatment with the highest germination and survival rates were ranked from highest to lowest: polyshade strips, polyshade cloth and, and American straw mat, with a survival rate of from eight to nine seedlings per meter. The soil temperatures and soil moisture contents vary greatly between the three treatments (Table 2 and 3), but under these row covers provided a suitable environment for guayule germination and establishment. The Agronet and Reemay row cover treatments also provided an environment suitable for guayule germination and establishment of seven to eight plants per meter despite having the highest soil temperature of all the treatments and varied soil moisture content. The no cover, first wheat and second wheat row cover treatments maintained temperatures in the imbibed seed, vermiculite covered; (FNI) surface fluid drilling of conditioned, nonimbibed seed, vermiculite covered; and (PP) 0-5 mm deep, no vermiculite, planting of conditioned, nonimbibed seed by a NIBEX cup feed distribution system, precision planter.

The two wheat row cover crops were planted on the outside edge of the beds. The first wheat planting was on January 22 and the second wheat planting on February 12. The wheat beds were planted at a rate of 126 seeds per meter with a Stanhay cone planter. The first and second wheat plantings received 100 mm post-plant irrigations. The wheat treatments were harvested on June 12 with the first wheat yielding 1292 kg per ha and the second wheat 983 kg per ha.

Conditioned seed was planted on April 7 at a rate of 46 seeds per meter, when the wheat plants were between 360 and 430 mm high. The seed was planted in 20 mm deep corrugations in the center of the beds, except for the American straw mat bed, which was left flat to provide direct contact between straw and seed bed. The conditioned seeds were treated by the Plant Molecular Genetics Laboratory, Beltsville, Maryland, using 25% polyethylene glycol (PEG, MW 8000, an osmoticum to prevent water uptake injury), 0.2% Thiram fungicide, adjusted to pH 8 with a saturated solution of $Ca(OH)_2$, 0.5 mg per ml KNO_3 (an oxidant), and .001 M gibberellic acid (GA, a growth hormone enhancing elongation) under a continuous light treatment for three to four days (Chandra et al. 1986). The conditioned seeds had a maximum laboratory germination rate of 79%. Row cover treatments were positioned over the appropriate treatment after seeding. A same-day irrigation was applied using a solid-set sprinkler system equipped with 3.2 mm inside diameter nozzles, spaced every 9 m along the pipeline. The irrigation schedule was daily for the first five days and then every second day for the remaining fifteen days. After establishment, flood irrigations were applied to extend the remaining five row cover treatments into a comparative study between field grown plants and transplanted seedlings.

Fifty lbs per acre ammonium nitrate fertilizer was applied (side dressed) on May 7. An application of Spectracide brand, 5% Diazinon granules at a rate of fourteen lbs per acre was made on April 10 to control a minor infestation of crickets and grasshoppers. Data collected included irrigation water applied, precipitation, meteorological data, soil moisture content, total soluble salts, soil temperature and plant stress data (Tables 1, 2, 3 and 5). Information was also recorded on seedling establishment and survival rates in the eight row cover treatments, taken 14, 31, 44, and 64 days after planting (Table 4).

As in the Fall 1986 experiment, a small duplication area was set up representing all treatments except the first and second wheat. A meteorological station equipped with a Campbell Scientific CR-21X data logger and multiplexer, measured air and soil temperatures, and bare soil net and solar radiation. In the first wheat plot a CR-21 data logger was set up to monitor soil temperatures and below canopy air temperature, relative humidity and solar radiation. In the second wheat plot a CR-21 data logger was set up to monitor below canopy height temperature, bare soil air temperature, relative humidity, solar radiation, wind speed and second wheat soil temperatures. These hourly measurements were converted to daily totals and averages (Tables 1 and 2).

Fall 1987

A sudan grass row cover crop was planted, prior to planting guayule seed, on the outside edges of the beds on August 31 at a rate of 46 seeds per meter with a Stanhay cone planter. The sudan grass received two 100 mm flood irrigations following planting (September 1 and 21), and was sprayed with a contact herbicide when 600 mm tall (September 22) to provide a crop-residue shade treatment.

The field, which was 56 m (48 beds) wide and 108 m long, was laid out in a strip-split plot statistical design with four replications. The first vertical strip treatments (row covers) were (NC) no cover, (CR) sudan grass shade crop residue and (SC) black Agronet coextruded polypropylene/nylon (solid cover, 20% shade); the second vertical strip treatments (irrigation levels) were (I-1) wet, (I-2) medium and (I-3) dry. Subplot treatments (planting depths) were (P-1) soil surface and (P-2) 10 mm deep. A preplant application of Diazinon granules was applied to the center of the beds at a rate of 17 kg per ha (15 lbs per acre). The surface and 10 mm deep seed was planted with a two row SV.255 GASPARDO vacuum planter at a rate of 46 seeds per meter (Figure 6).

The guayule seed was planted on September 30, 1987, on the soil surface, or 10 mm deep and covered with soil. The seed was conditioned at the Plant Molecular Genetics Laboratory, Beltsville, Maryland in the same manner as the spring 1987 conditioned seed. The conditioned seed had a maximum germination rate of 52%. The Agronet row cover was positioned over the appropriate treatment after seeding. No fertilizer was applied. An infestation of flea beatles, corn ear worms and cabbage worms from adjacent fields of cotton and vegetable crops resulted in the applications of liquid Diazinon (.950 L per 190 L of water) on October 5 and liquid Lannate (1.2 L per 190 L of water) on October 7, 8, 10, 12, 15 and 20.

Irrigation water was delivered through 10 mil Chapin Twin Wall IV drip irrigation tubing, outlet spacing every 150 mm (6 in), delivered at 0.093 L per min per meter (75 gpm per 100 linear feet). Water applications were measured through a 25 mm (1 in) diameter propeller-type water meter. All plots were irrigated daily for the first five days, then every 2 (I-1), 4 (I-2) or 6 (I-3) days, followed by every 3 (I-1), 6 (I-2) or 9 (I-3) days (Table 9).

Data collected included irrigation water applied, precipitation, meteorological data, soil moisture content and total soluble salts. Information was also recorded on seedling establishment and survival rates for the three treatment levels (Figs. 3, 4, and 5). Mean number of seedlings per 15 m for the row covers treatments, irrigation levels and planting depths are listed in Table 11. A meteorological station equipped with a Campbell Scientific CR-21 data logger, measured air temperature, relative humidity and solar radiation (Table 9).

Transplant - Direct Seeding Comparison

The direct seeding phase of the experiment was completed on the June 11 plant count date. Row cover treatments (A) no cover, (B) first wheat and (C) second wheat were eliminated because of the lack of plants. All row covers had been removed from the remaining five treatments: (D) Agronet, (E) Reemay, (F) polyshade cloth, (G) polyshade strips and (H) American straw mat by May 21. The plants in these five treatments were carried over and used in a comparative experiment with greenhouse grown transplants.

The greenhouse grown plants were started from nonconditioned guayule seed on the same day the field direct seeding experiment was planted (April 7). The transplant treatments consisted of plants grown in the U.S. Cotton Research Center, Phoenix, Arizona greenhouses under enriched CO_2 and with no CO_2, and plants grown in the U.S. Water Conservation Laboratory, Phoenix, Arizona greenhouse with no CO_2. Table 7 lists the planting methods and will be referred to hereafter as (CRC CO_2), (CRC no CO_2) and (WCL no CO_2).

The guayule seeds were planted in a peat, vermiculite and pearlite potting soil and transferred to speedling trays when in the two to three leaf stage and then fertilized with Hoagland's fertilizer solution every seven to ten days. The transplants were planted on June 10 in the 14 m by 22 m site previously used for the direct seeding experiment CR-21X meteorological station row cover treatment duplication area. Surface flood irrigations were scheduled to establish the greenhouse transplants and maintain existing field direct seeded plants. Precipitation for this period was 27.2 m (Table 6). Data collected included plant counts, plant growth, rubber and resin content, soil water content and total soil salts. Growth rates were recorded monthly, for four months, from the day the greenhouse grown seedlings were transplanted (Table 7).

RESULTS AND DISCUSSION

Spring 1987

The total irrigation water applied was 150 mm from April 8 to May 6 with no measurable precipitation noted. The spring 1987 establishment irrigation amount was a departure (50% increase) from a drier irrigation regime in the summer of 1986, primarily to provide a moist bed for the 0-5 mm deep planted, conditioned, nonimbibed seed and provide adequate moisture for actively growing wheat row cover crops. The added spring 1987 irrigation level did promote high overall germination and survival rates in precision planted rows, but was detrimental to the fluid drilled, imbibed rows (Fig. 3, 4 and 5). The two-weeks-after-planting seedling counts, revealed that the spring 1987 precision planted, conditioned seed treatment had a survival rate 65% higher than the best summer 1986 treatment (conditioned fluid drilled seed in wheat cover, under dry irrigation).

Table 4 presents guayule seedling counts for four selected dates. Guayule seed germination (initial emergence) was essentially complete for the fluid drilled, imbibed seed on April 13, six days after planting, and on April 17, ten days after planting for the fluid drilled nonimbibed and precision planted nonimbibed seed. Figures 3, 4, and 5 represent guayule seedling counts on the number of plants per 15 m distances for three planting methods across eight row cover treatments, replicated four times.

The first month establishment period and the following survival period presented fairly consistent trends between the planting methods and eight row cover treatments. Limited reference is made of row cover treatments A (bare soil), B (first wheat) and C (second wheat) because of unsatisfactory survival rates. The remaining five row cover treatments D (Agronet), E (Reemay), F (polyshade cloth), G (polyshade strips) and H (American straw mat) were carried into October as a part of a comparative study including greenhouse grown transplants. The first establishment plant count did not include the H (American straw mat) row cover treatment because the guayule seedlings had not emerged through the straw mat.

For the three planting methods FI (fluid drilled, imbibed), FNI (fluid drilled nonimbibed) and PP (Nibex precision planter), the precision planted seeds had an average of 85% increased plant emergence and survival rate over the combined average fluid drilled seed (Table 4). The trend, over time, was for a slight die off of seedlings during the first month establishment period, followed by a dramatic decline into the second month and then a more gradual die off (Table 4). Stand counts for the five row cover treatments carried into October are given in Figs. 3, 4 and 5 for the three planting methods. For the specific row cover treatments averaged over the three planting methods the survival ranking remained constant from the first count, taken two weeks after planting, and the final count, taken seven weeks after planting (Table 4). Final count, ranked from best to worst, were as follows; G (polyshade strips) 10.6 seedlings per meter, F (polyshade cloth) 8.5 seedlings per meter, H (American straw mat) 7.2 seedlings per meter, D (Agronet 7.7 seedlings per meter, E (Reemay 7.2 seedlings per meter, C (second planted wheat) 1.7 seedlings per meter, B (first planted wheat) 1.6 seedlings per meter, and A (bare soil) 0.3 seedlings per meter.

The soil water content measurements for the eight cover treatments are shown in Table 3. The samples were taken prior to irrigations on twelve collected dates at 0-30 and 30-50 mm depths, including a preplant sample which reflects a field average. The mean rating over some evaporating moisture, reduces UV radiation and protects the seedlings from wind and blowing soil particles.

Fall 1987

The total irrigation water applied for the three irrigation levels was 63.5 mm (I-1), 43.2 mm (I-2) and 35.6 mm (I-3) from October 1 to October 28 with a total of 37.6 mm precipitation. At the 0-20 mm soil depth, the soil water data reflects the anticipated overall water content trends under the three row cover treatments, ranked from high to low: Agronet, bare soil and sudan grass, and three irrigation levels, ranked from high to low: wet, medium and dry. Historical data and actual plant response to irrigation levels indicated that the wet and medium treatments provided too much water to the seedlings, with the dry treatment providing the most appropriate soil moisture content (Table 10). Also, the plant count data analysis showed no significant difference between the three irrigation levels at a .05 confidence level. Irrigation water and total soluble soil salts were in an acceptable range throughout the experiment with an average of 696 ppm irrigation water and an overall field average of 1257 ppm total soluble salts in the soil (Fig 2).

Table 11 presents mean seedling survival rates for the three treatment levels for five selected dates. Guayule seed emergence (initial emergence) was first noted four days after planting and was essentially completed on the sixth day. There was a significant difference in plant survival between the two planting depths and between the three row cover treatments (Figs 3 and 5). Irrigation levels presented no significant differences in stand establishment. On the final count date (November 5) the 10 mm deep treatment showed a survival rate 59% higher than the 0 mm depth (5.5 vs 3.5 seedlings per meter). On the same counting date the Agronet and no cover treatments survival rates were essentially the same (5.7 vs 5.5 seedlings per meter), but both Agronet and no cover row cover treatments resulted in a 150% increase in stand over the sudan grass (5.6 vs 2.3 seedlings per meter).

A comparison between the optimum, comparable treatments between Fall 1987 (Agronet, precision planted, 10 mm deep over three irrigation levels) and spring 1987 (Agronet, precision planted, 0-5mm deep one irrigation treatment) shows a decline in seedling survival in the Fall 1987. By the second week after planting, the Fall 1987 count showed a 41% lower survival rate than the spring 1987 count (13.3 vs 22.7 seedlings per meter), and four weeks after planting the difference was 75% lower (5.7 vs 23.3 seedlings per meter). The differences reflect, in general, more suitable planting conditions for guayule in the spring. In the spring in central Arizona we have a much lower insect population, warmer, more stable temperatures and reduced wind duration and intensity.

The Fall 1987 weather data (Table 9) is limited, but does present the drop in above ground temperatures and increase in relative humidity through the month of October and the precipitation and associated cloudy days during the second and fourth weeks of the month.

Transplant - Direct Seeding Comparison

Differing cultural and/or environmental factors between the CRC and WCL greenhouses produced, on the average, 200% larger (by weight) plants in the CRC greenhouse, regardless of CO_2 levels. On transplanting day the CRC CO_2 and no CO_2 plants were 100% larger (by weight) than the field direct seeded plants but by the end of the four month experiment (October 14) the field direct seeded plants were 18% larger (by weight) than the averaged CRC CO_2 and no CO_2 plants (Table 7). The CRC CO_2 plants had a dry weight 40% heavier than the no CO_2 plants on June 10 but only 5% heavier on October 14. The values given for the root concentrations (gm dry weight/mm root length) relate only to the fact that the field direct seeded plant roots were typically well formed aggressive taproots. Whereas the CRC and WCL transplants were a more fibrous, shallow growing root system with resultant higher root concentration values. On the final sampling date, plants were harvested for rubber and resin analysis (Table 7). The field direct seeded, six month old whole plants contained 20% more rubber than the average combined CRC CO_2, CRC no CO_2 and WCL no CO_2 plants (1.6% vs 1.3%).

Following the field establishment of the transplants, the soil water content readings were similar between field direct seeding and transplant plots. Total soluble soil salts remained within acceptable levels at the 0-75 mm depth (Table 6). Table 8 presents the survival rates of six month old field direct seeded plants and greenhouse started transplants from date of transplant (June 11) to end of experiment (October 14). At a .36 m (14 inch) spacing (45 plants/m) the CRC CO_2 plants had a survival rate equal to the combined five row cover crop treatments (81%). The averaged CRC no CO_2 and WCL no CO_2 plants survival rate was 28% lower that the CRC CO_2 plants (64% vs 82%).

This lower survival rate can be explained, in part, by the measurements and observations at transplanting (Table 8). The CRC no CO_2 and WCL no CO_2 plants were on the average 50% smaller on weight and had less developed root systems than the CRC CO_2 plants. For all treatments, the stand in plants/m was in an acceptable range. The field direct seeded plants had an average of 7 plants/m, the CRC CO_2 had 2.5 plants/m and the CRC no CO_2 and WCL no CO_2 had 2 plants/m.

SUMMARY AND CONCLUSIONS

Spring 1987

The ability to establish uniform plant stands of guayule has been enhanced with the use of natural and synthetic row cover crops. The benefits of using seed conditioned with polyethylene glycol, gibberellic acid and light are now well established and the spring 1987 experiment indicates precision planting of nonimbibed, conditioned seed may be superior to planting by fluid drilling methods. In the spring 1987 in Central Arizona, precision planted nonimbibed seed out-performed the fluid drilled imbibed and nonimbibed seed. The precision planted polyshade strips, polyshade cloth and American straw mat provided excellent stands of guayule, the Reemay and Agronet had acceptable stands, and the no cover, first wheat and second wheat unacceptable stands. Water management was a problem during the spring 1987 experiment. Even under a program of frequent, higher application rates of water, the soil moisture content dropped rapidly two weeks after planting. The total irrigation amount of 150 mm for the month was also an inadequate amount to establish guayule in a nurse cover crop of actively growing wheat. The wheat, itself, utilized the irrigation water, yielding 1293 kg per ha for the first planting and 938 kg per ha for the second planting.

Fall 1987

As in the spring 1987, guayule seed was planted under a synthetic row cover as well as a shade crop residue to test the ability of these treatments to enhance the establishment of conditioned, nonpregerminated seed. Additional variables were included to examine the effects of irrigation levels and a 10 mm planting depth. One month after planting, the 10 mm planting depth had on average 5.7 seedlings per meter as opposed to 23.3 seedlings per meter for the comparable spring 1987 Agronet row cover treatment and 9.3 seedlings per meter for the spring 1987 no cover treatment. The fall 1987 stand count failed to take into account the anticipated loss of 50% or more of the plants through the fall and winter. The sudan grass shade crop residue's poor performance can be attributed to a number of factors. The first being the infestation of corn ear worms and cabbage worms that became established in the crop residue and under the drip tubing. Secondly the sudan grass disintegrated during the first week of planting due to extremely high winds, because it failed to develope rigid stalks at the desired height and canopy development stage. The irrigation level data indicated a need to develop optimum scheduling of irrigation amounts and timing. A guayule direct seeding study in the spring of 1988 at Maricopa, Arizona, will examine the effects of six irrigation levels and three row cover treatments; (1) no cover, (2) vermiculite mulch cover and (3) Agronet coextruded polypropylene/nylon cloth (20% shade) on seedling establishment.

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Table 1. Weekly average water application, precipitation, air temperatures, relative humidity, solar radiation, and net radiation in the Spring 1987 at the Maricopa Agricultural Center.

			Air Temperature 150 mm Height						Relative Humidity 150 mm Height						Solar Radiation 100 mm Height Joules/m²/Day			Net Radiation 1.5 m Height Joules/m²/Day	Wind 2.0 m Height	
			No Cover			First Wheat Cover			No Cover			First Wheat Cover			No Cover	First Wheat Cover	Second Wheat Cover	No Cover	M/S	
Date	Water Applied3/ (mm)	Precip-tation (mm)	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg					Avg	Max
8 Apr-14 Apr2/	63.2	-	31.2	10.5	20.2	28.4	6.9	17.2	60.1	11.2	31.4	92.8	29.0	63.7	27.8	22.1	19.4	17.3	2.2	4.3
15 Apr-21 Apr	30.2	-	33.3	10.6	27.1	26.3	8.6	19.2	54.0	9.6	23.4	89.0	26.9	56.1	27.2	19.0	17.4	15.0	1.9	3.9
22 Apr-28 Apr	27.7	-	35.5	15.3	25.0	33.0	14.0	22.3	58.5	11.8	30.1	92.3	33.1	66.4	25.8	17.7	16.0	13.7	2.3	4.9
29 Apr-5 May1/	29.0	-	34.6	13.1	23.9	33.8	13.0	22.3	73.1	10.8	33.6	89.1	20.6	57.8	28.5	19.8	19.1	15.5	2.2	4.5
Total or Average	150.1		33.7	12.4	22.8	30.4	10.6	20.3	61.4	10.9	29.6	90.8	27.4	61.0	27.3	19.7	18.0	15.4	2.2	4.4

1/ Average of 8 days (all row cover treatments).
2/ Three days data missing on first wheat planting (Apr 10, 11, 12).
3/ First wheat irrigated on Jan 22, 102 mm, second wheat irrigated on Feb 12; 102 mm, direct seed preplant irrigation on Mar 27, 102 mm.

Table 2. Guayule seedling counts per a 15 m distance for four selected dates with eight row cover treatments and three planting methods in the Spring 1987 at the Maricopa Agricultural Center.

Variables	Counting Dates 4/21	5/8	5/21	6/10	Final Rank 4/
	No. of Seedlings per 15 m Distance 5/				
Row Cover Treatment 1/					
(A) No Cover (check)	89	75	7	5	8
(B) First Wheat Crop	113	50	36	24	7
(C) Second Wheat Crop	92	49	38	26	6
(D) Agronet (10% shade)	182	160	122	117	4
(E) Reemay (20% shade)	186	160	133	110	5
(F) Polyshade Cloth (40% shade)	205	201	139	129	2
(G) Polyshade Strip (40% shade)	234	238	174	161	1
(H) American Straw Mat	-- 2/	206	144	118	3
Surface Planting Method 3/					
(P_1) Fluid Drilled, Imbibed Conditioned Seed	134	126	89	78	2
(P_2) Fluid Drilled, Nonimbibed Conditioned Seed	108	103	72	52	3
(P_3) Precision Planted, Nonimbibed Conditioned Seed	229	198	137	119	1

1/ Mean of 12 counting plots (three planting methods times four replications) for each row cover treatment.
2/ Seedlings had not yet protruded above the straw cover and could not be counted at this early date.
3/ Mean of 32 counting plots (eight row cover treatments times four replications) for each surface planting methods.
4/ Ranking of seedling counts was from highest to lowest.
5/ Planting rate of 46 seed/m.

Table 3. Soil water contents by weight, % taken before irrigation, for eight row cover treatment at 0-30 mm and 30-50 mm soil depths in the Spring 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

Row Cover Treatment							0-30 mm Soil Depth							
Date	4/7 1/	4/9	4/13	4/17	4/20	4/22	4/24	4/27	5/1	5/4	5/8	5/21	Mean	Rank
(A) No Cover	5.0	16.6	7.4	8.1	6.2	5.8	6.5	7.6	9.2	9.3	5.4	11.3	8.5	6
(B) First Wheat	---	19.7	8.4	9.1	6.0	4.7	5.0	6.4	9.0	5.5	5.3	7.1	7.7	8
(C) Second Wheat	---	22.1	5.5	7.3	7.8	4.8	4.0	8.8	8.3	5.9	4.2	12.0	8.2	7
(D) Agronet	---	18.2	9.0	10.2	12.1	10.1	9.3	7.4	8.3	7.1	4.2	7.8	9.4	5
(E) Reemay	---	19.3	14.7	15.3	8.8	7.2	6.9	7.6	13.9	11.7	6.5	9.8	11.1	3
(F) Polyshade Cloth	---	19.5	10.9	13.8	8.2	8.7	10.4	10.4	12.4	12.3	9.2	11.0	11.5	2
(G) Polyshade Strips	---	19.6	10.0	9.7	7.7	8.4	9.7	8.0	11.2	7.2	5.5	7.7	9.5	4
(H) American Straw Hat	---	20.4	11.8	17.8	14.7	13.0	14.7	16.5	12.9	10.7	7.8	10.4	13.7	1
Mean	5.0	19.4	9.7	11.4	8.9	7.8	8.3	9.1	10.7	8.7	6.0	9.6		
							30-50 mm Soil Depth							
(A) No Cover	8.0	18.1	15.5	15.1	12.3	11.4	13.7	12.3	11.5	11.1	10.9	15.0	13.3	5
(B) First Wheat	---	19.1	12.2	13.7	10.8	8.6	8.7	7.2	12.0	9.7	8.3	15.1	11.4	7
(C) Second Wheat	---	22.0	13.1	11.6	12.1	8.7	6.1	10.2	10.7	10.0	7.1	12.8	11.3	8
(D) Agronet	---	19.2	15.1	14.3	13.4	12.4	14.5	12.6	10.5	8.8	7.2	12.6	12.8	6
(E) Reemay	---	19.4	17.8	17.5	14.3	13.9	13.6	13.7	15.2	13.7	12.9	15.5	15.2	2
(F) Polyshade Cloth	---	19.3	16.3	16.3	14.7	14.2	14.3	16.4	14.2	11.2	13.4	13.5	14.9	3
(G) Polyshade Strips	---	20.2	16.6	16.4	14.3	13.6	13.8	11.7	14.0	11.7	11.4	12.0	14.2	4
(H) American Straw Hat	---	20.3	14.8	19.0	17.0	15.4	15.4	16.9	17.8	12.7	13.4	15.1	16.2	1
Mean	8.0	19.7	15.2	15.5	13.6	12.3	12.5	12.6	13.2	11.6	10.6	14.0		

1/ Average soil water content taken before applying a preplant irrigation and beginning of row cover treatments.

Table 4. Weekly average soil temperatures at 10 and 30 mm soil depths for eight row cover treatements in the Spring 1987 at the Maricopa Agricultural Center.

ROW COVER TREATMENT[3/]

Date	(A) No Cover						(B) First Wheat Planting					
	1 cm			3 cm			1 cm			3 cm		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
8 Apr-14 Apr[2/]	28.7	10.2	18.3	25.3	11.9	18.2	25.9	10.2	16.8	25.5	12.3	17.7
15 Apr-21 Apr	31.2	11.8	17.1	27.6	13.4	17.0	29.1	12.4	19.0	25.6	13.4	18.4
22 Apr-28 Apr	34.5	16.1	23.4	31.0	17.5	20.0	32.6	17.4	22.8	29.4	17.7	22.0
29 Apr-6 Mar[1/]	34.4	16.5	24.1	30.9	18.0	23.8	34.0	17.8	23.8	31.9	18.1	23.4
Average	32.2	13.7	21.5	28.8	15.3	21.4	31.0	15.1	21.2	28.5	15.8	20.8

Date	(C) Second Wheat Planting						(D) Agronet					
	1 cm			3 cm			1 cm			3 cm		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
8 Apr-14 Apr[2/]	27.6	11.5	14.8	25.5	13.0	18.1	33.5	12.5	20.8	28.3	14.1	20.6
15 Apr-21 Apr	29.8	12.2	19.0	26.8	11.7	19.2	33.6	11.5	21.9	29.6	14.9	18.5
22 Apr-28 Apr	34.2	16.4	19.3	30.2	17.5	22.3	37.2	17.1	24.8	32.0	18.5	24.2
29 Apr-6 Mar[1/]	33.9	16.2	23.3	31.5	17.7	23.2	35.3	17.4	24.7	31.2	18.5	24.2
Average	31.7	14.2	20.8	28.7	15.6	20.9	34.3	15.2	23.1	30.3	16.6	22.7

Date	(E) Reemay						(F) Polyshade Cloth					
	1 cm			3 cm			1 cm			3 cm		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
8 Apr-14 Apr[2/]	31.5	13.0	20.9	28.7	13.4	20.7	27.3	11.9	18.9	25.3	13.2	16.2
15-Apr-21 Apr	32.8	13.2	21.4	29.6	13.8	21.2	30.0	12.3	19.4	26.2	13.4	19.2
22 Apr-28 Apr	35.4	17.6	24.5	32.5	17.7	24.1	32.1	16.1	22.4	29.1	17.0	22.1
29 Apr-6 Apr[1/]	34.8	17.6	24.6	31.8	17.8	24.3	32.4	16.5	23.1	29.6	17.5	22.9
Average	33.7	15.4	22.9	30.7	15.8	22.6	30.3	14.3	21.0	27.6	15.4	20.9

Date	(G) Polyshade Cloth Strips						(H) American Straw Mat					
	1 cm			3 cm			1 cm			3 cm		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
8 Apr-14 Apr[2/]	28.2	10.8	18.6	25.4	12.1	18.4	24.7	12.1	17.4	22.6	13.4	17.6
15-Apr-21 Apr	30.9	11.7	19.7	27.3	13.2	19.6	25.3	12.6	18.0	22.6	13.7	18.0
22 Apr-28 Apr	34.2	15.9	22.9	25.3	17.1	22.6	27.7	16.1	20.8	25.2	17.0	20.7
29 Apr-6 Apr[1/]	35.4	16.2	23.8	30.7	17.5	23.5	28.5	16.4	21.5	25.9	17.3	21.4
Average	32.3	13.7	21.3	28.4	15.1	21.1	26.6	14.4	19.5	24.1	15.4	19.5

1/ Average of 8 days (all row cover treatments).
2/ Three days data missing on First Wheat Planting (Apr 10, 11, 12).
3/ Guayule seeds were planted on Apr 7 and row cover treatments installed on the same day. Straw mat removed on May 11, remaining covers removed on May 21.

Table 5. Guayule seedling water potential, cotyledon temperature, air temperature, soil surface temperature and soil water content for three dates prior to irrigations on five shade treatments in the Spring 1987 at the Maricopa Agricultural Center.

Row Cover Treatment	Seedling Water Potential - Bars					Cotyledon, Under Surface Temperature (5 mm Aboveground) °C					Air Temperature (5 mm Aboveground) °C				
	4/22	4/27	5/4	Mean	Rank1/	4/22	4/27	5/4	Mean	Rank3/	4/22	4/27	5/4	Mean	Rank3/
(A) No Cover	-16.3	-15.0	-15.9	-15.7	4	35.0	38.4	38.6	37.3	4	33.5	38.1	38.2	36.6	2
(B) First Wheat	-16.5	-19.8	-24.7	-20.4	5	36.7	36.9	40.0	37.9	5	36.0	37.1	38.6	37.2	4
(D) Agronet	-11.7	-13.4	-13.6	-12.9	1	36.2	37.2	35.3	36.2	3	37.4	39.1	39.4	38.6	5
(F) Polyshade Cloth	-13.9	-12.8	-13.8	-13.5	2	33.8	35.5	34.6	34.6	2	34.4	37.4	39.4	37.1	3
(H) American Straw Mat	-13.6	-14.8	-12.7	-13.7	3	32.2	34.1	33.2	33.2	1	31.4	34.6	34.0	33.3	1

Row Cover Treatment	Soil Surface Temperatures2/ (Under Row Cover Treatments) °C					Soil Water Content % By Weight Preirrigation Samples (0-30 mm Depth) %					Soil Water Content % By Weight Preirrigation Samples (30-50 mm Depth) %				
	4/22	4/27	5/4	Mean	Rank3/	4/22	4/27	5/4	Mean	Rank4/	4/22	4/27	5/4	Mean	Rank4/
(A) No Cover	39.4	42.3	43.5	41.7	4	5.8	7.6	9.3	7.6	4	11.4	12.3	11.1	11.6	3
(B) First Wheat	35.6	37.7	49.9	41.1	3	4.7	6.4	5.5	5.5	5	8.6	7.2	9.7	8.5	5
(D) Agronet	41.5	44.9	43.2	43.2	5	10.1	7.4	7.1	8.2	3	12.4	12.6	8.8	11.3	4
(F) Polyshade Cloth	29.8	33.4	40.9	34.7	2	8.7	10.4	12.3	10.5	2	14.2	16.4	15.2	15.3	1
(H) American Straw Mat	26.3	31.1	33.7	30.4	1	13.0	16.5	10.7	13.4	1	15.4	16.9	12.7	15.0	2

1/ Rankings of seedling water potentials is from the lowest to highest water stress.
2/ Soil temperatures taken with infrared thermometer.
3/ Rankings of cotyledon, air, and soil temperatures is from coolest to hottest temperature.
4/ Rankings of soil water content is from the wettest to driest value.

Table 6. Weekly average water applications, precipitation, soil water content by weight (%), and total soluble salts mg/l for a comparative experiment between direct seeded and transplanted guayule seedlings in the Summer 1987 at Maricopa Agricultural Center.

	Water Applied (mm)		Precipitation (mm)	Soil Water Content by Weight (%)				Total Soluble Salts (mg/l)	
				Direct Seeded		Transplanted		Direct Seeded	Transplanted
Date	Direct Seeded1/	Transplanted		0-75 mm	0-150 mm	0-75 mm	0-150 mm	0-75 mm	0-75 mm
Jun 4 - Jun 10 2/ 3/	100	100	-	9.8	13.7	13.9	16.4	1605	1145
Jun 11 - Jun 17	-	150	-	-	-	15.1	18.0	-	-
Jun 18 - Jun 24	-	50	-	7.7	12.1	16.6	19.3	1709	905
Jun 25 - Jul 1	-	-	-	-	-	-	-	-	-
Jul 2 - Jul 8	-	-	-	-	-	-	-	-	-
Jul 9 - Jul 15	-	-	-	-	-	-	-	-	-
Jul 16 - Jul 22	-	-	-	-	-	-	-	-	-
Jul 23 - Jul 29	-	-	4.6	6.1	8.6	6.4	8.6	-	-
Jul 30 - Aug 5	100	100	-	-	-	-	-	-	-
Aug 6 - Aug 12	-	-	-	-	-	-	-	-	-
Aug 13 - Aug 19	-	-	3.0	-	-	-	-	-	
Aug 20 - Aug 26	-	-	19.6	9.7	11.5	10.5	11.6	-	-
Aug 27 - Sep 2	100	100	-	-	-	-	-	-	-
Total or Average	300	500	27.2	8.3	11.5	12.5	14.8	1657	1025

1/ A total of 350 mm of irrigation water was applied to the direct seeding experiment between Apr 7 and Jun 3, prior to the transplant phase.
2/ Total field pretransplant irrigation and pretransplant soil water content, and total dissolved solids samples.
3/ Transplants field planted on Jun 10, 1987.

Table 7. Seedling growth for direct seeded and transplanted guayule seedlings in the Summer 1987 at the Maricopa Agricultural Center.

Seedlings	Top Growth Sampling Date										Root Concentration 200 mm Deep	Whole, Six-month-old Plants Resin Content	Whole, Six-month-old Plants Rubber Content
	6/10/87		7/14/87		8/12/87		9/10/87		10/14/87		10/14/87	10/14/87	
	Height (mm)	Weight (gm)	Height (mm)	Weight (gm)	Height (mm)	Weight (gm)	Height (mm)	Weight (gm)	Height (mm)	Weight (gm)	gm/mm	%	%
Direct Seeded	71	0.3[1/]	118	3.7[2/]	230	17.5[3/]	359	36.1[3/]	362	49.1[3/]	27[6/]	4.6	1.6
Transplants													
Cotton Research Center Greenhouse, Phoenix, AZ CO₂ Enriched [4/]	103	0.7	112	2.7	155	7.5	247	33.0	227	42.8	28[7/]	5.6	1.2
No CO₂ (Check) [4/]	112	0.5	117	2.0	142	9.3	232	25.8	253	40.7	37[7/]	5.6	1.4
U.S. Water Conservation Laboratory Greenhouse, Phoenix, AZ No CO₂ (Check) [5/]	73	0.2	74	0.5	100	2.8	147	6.3	158	14.8	23[7/]	6.8	1.4

1/ Average of three plants per eight row cover treatments over three planting methods, direct seeded plants.
2/ Average of three plants per seven row cover treatments over three planting methods (too few plants in no cover to sample), direct seeded plants.
3/ Average of three plants per five row cover treatments over three planting methods (too few plants in first and second wheat cover to sample), direct seeded plants.
4/ Average of six plants per counting date.
5/ Average of twelve plants per counting date.
6/ Plants developed tap roots.
7/ Plants developed fibrous roots.

Table 8. Guayule plant counts at two and six months age, reflecting survival rates over transplant phase of experiment, Summer 1987, at the Maricopa Agricultural Center.

Variables	Counting Dates 6/11	10/14	Survival Rate (%)
	No. of Plants per 15 m Distance		
Direct Seeded Shade Treatments 1/			
Agronet	117	91	78
Reemay	110	102	93
Polyshade Cloth	129	106	82
Polyshade Strips	161	118	73
American Straw Mat	118	95	81
Mean	127	102	81
Greenhouse Started Transplants 2/			
CO_2 Enriched	45	37	82
Check	45	29	64
WCL	45	29	64

1/ Field direct seeded on 4/7/87; no cover, first wheat, and second wheat eliminated after initial establishment period.

2/ Greenhouse seeded on 4/7/87, and transplanted into field plots on 6/10/87.

Table 9. Weekly average water application, precipitation, air temperature, relative humidity and solar radiation in the Fall 1987 at the Maricopa Agriculture Center, Maricopa, Arizona.

Date	Water Applied (mm) Wet	Medium	Dry	Precipitation	Air Temperature 1.2 M Height No Cover			Relative Humidity 1.2 M Height No Cover			Solar Radiation 100 cm Height Joules/m²/day No Cover
	I_1	I_2	I_3	(mm)	Max	Min	Avg[5/]	Max	Min	Avg[5/]	
1 Oct - 7 Oct[1/2/]	30.5	25.4	25.4	-	38.3	13.7	25.2	62.4	7.6	25.2	27.6
8 Oct - 14 Oct	20.3	10.2	5.1	2.0	34.3	14.4	23.6	69.3	14.1	23.6	22.4
15 Oct - 21 Oct	10.2	5.1	5.1	-	33.7	10.5	21.1	67.1	9.8	32.6	24.2
22 Oct - 28 Oct[3/4/]	2.5	2.5	-	3.3	30.8	15.3	21.8	85.9	21.9	57.9	16.3
Totals and Averages	13.5	43.2	35.6	37.6	34.3	13.5	22.9	71.2	7.6	34.8	22.6

1/ All three irrigation treatments (I_1, I_2, and I_3) received the same amounts of water for the first five days, Oct 1 - Oct 5.

2/ Irrigation treatments started on Oct 6 of even 2 (I_1), 4 (I_2) and 6 (I_3) days.

3/ Due to excessive water being applied, irrigation schedule days extended to 3 (I_1), 6 (I_2), and 9 (I_3) days.

4/ Irrigations discontinued on Oct 22 due to excessively wet soil and precipitation.

5/ Averages reflect averages of 24 hourly readings.

Table 10. Soil water content by weight, % taken prior[4/] to and during irrigation treatments[5/] for three irrigation levels over three row cover treatments at 0-20, 0-50, and 0-80 mm soil depths in the Fall 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

	Date	9/30	10/2	10/6	10/9	10/15	10/22	10/27	Mean	Rank
0-20 mm Soil Depth										
Row Cover Treatment[1/]										
No Cover (NC)		6.2	11.5	14.9	10.5	7.5	6.1	8.4	9.3	2
Sudan Grass (CR)		4.1	13.0	15.2	9.1	7.8	5.6	8.9	9.1	3
Black Agronet (SC)		6.3	14.4	16.7	10.8	10.4	6.9	10.8	10.9	1
	Mean	5.5	13.0	15.6	10.1	8.6	6.2	9.4		
Irrigation Treatments[2/]										
I_1 Wet		[3/]	-	16.9	12.6	12.0	8.4	10.1	12.0	1
I_2 Medium		-	-	15.9	11.0	9.0	5.8	10.2	10.4	2
I_2 Dry		-	-	14.0	6.9	4.5	4.4	7.7	7.5	3
	Mean			15.6	10.2	8.5	6.2	9.3		
0-50 mm Soil Depth										
Row Cover Treatment[1/]										
No Cover (NC)		9.7	12.4	16.4	13.5	11.1	11.2	10.7	12.1	2
Sudan Grass (CR)		5.8	13.2	15.8	14.0	7.1	9.4	10.2	10.8	3
Black Agronet (SC)		7.8	14.6	16.7	13.1	11.8	10.4	11.2	12.2	1
	Mean	7.8	13.4	16.3	13.5	10.0	10.3	10.7		
Irrigation Treatments[2/]										
I_1 Wet		[3/]	-	17.1	14.4	13.1	12.1	12.3	13.8	1
I_2 Medium		-	-	16.1	13.4	11.0	10.2	11.2	12.4	2
I_3 Dry		-	-	15.8	12.8	8.7	8.8	8.7	11.0	3
	Mean			16.3	13.5	10.9	10.4	10.7		
0-80 mm Soil Depth										
Row Cover Treatment[1/]										
No Cover (NC)		11.0	13.4	16.9	14.4	12.0	11.9	12.1	13.1	1
Sudan Grass (CR)		6.9	13.1	15.9	12.8	11.7	10.6	11.6	11.8	3
Black Agronet (SC)		9.5	14.4	16.9	14.3	12.9	11.0	11.8	13.0	2
	Mean	9.1	13.6	16.6	13.8	12.2	11.2	11.8		
Irrigation Treatments[2/]										
I_1 Wet		[3/]	-	17.0	15.4	14.1	12.9	16.3	15.1	1
I_2 Medium		-	-	16.7	14.4	12.5	10.7	11.7	13.2	2
I_3 Dry		-	-	16.0	11.7	10.0	9.8	10.4	11.6	3
	Mean			16.6	13.8	12.2	11.1	12.8		

1/ Averaged over three irrigation treatments.

2/ Averaged over three shade cover treatments.

3/ Irrigation treatments not started until 10/5/87.

4/ I_1, I_2, and I_3 treatment levels received the same amounts of water during the first five days after planting.

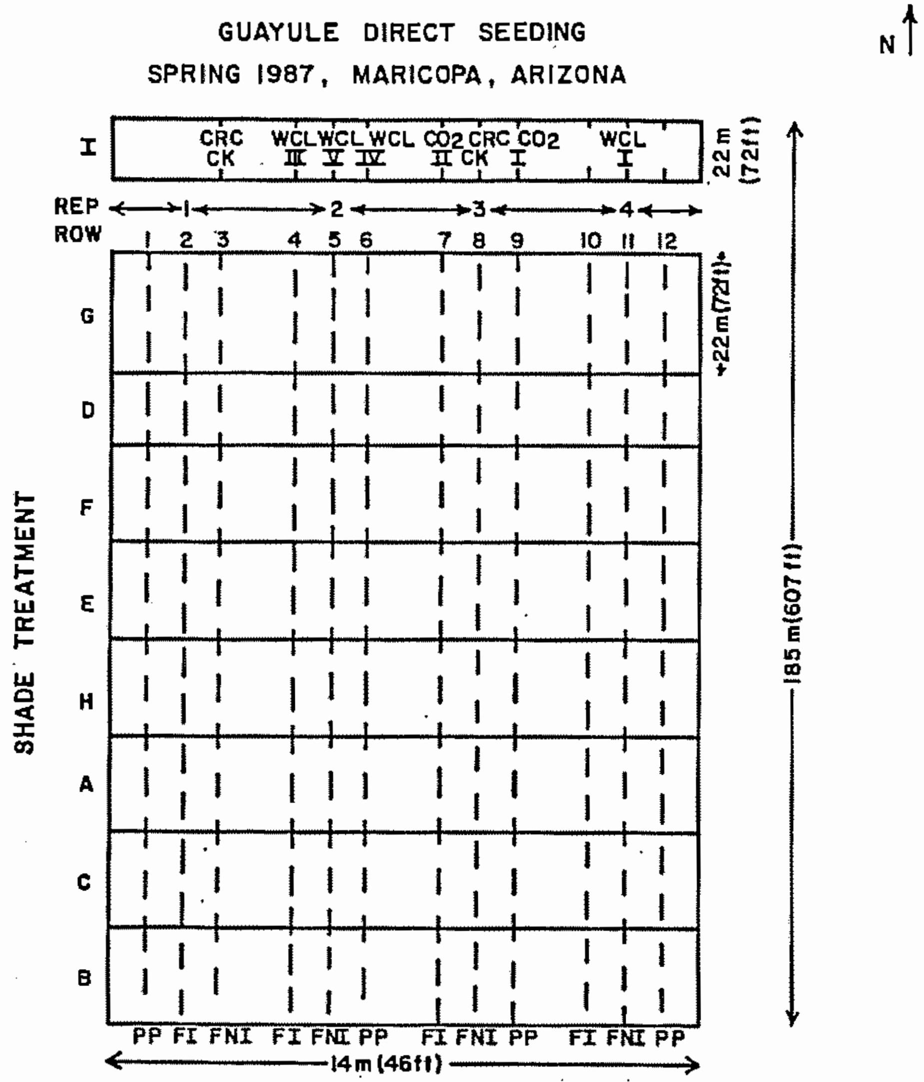
5/ Irrigation treatments started on 10/5/87.

Table 11. Guayule seedling counts per a 15 m distance for five selected dates with planting depths, row cover treatments, and irrigation levels at Maricopa Agricultural Center for conditioned cv. 11591 seeds planted on September 30, 1987.

	Counting Dates				
Treatments[1/]	10/8/87	10/15/87	10/22/87	10/29/87	11/5/87
Planting Depth					
0 mm	127 A*	88 A	65 A	57 A	52 A
10 mm	202 B	148 B	111 B	97 B	83 B
Row Cover Treatments					
Agronet (20% Shade, Full Cover)	192 A	152 A	114 A	102 A	86 A
No Cover	171 AB	133 A	109 A	94 A	83 A
Crop Residue	130 B	70 B	41 B	34 B	34 B
Irrigation Levels					
I_1 (Wet)	174 A	122 A	85 A	69 A	62 A
I_2 (Medium)	160 A	122 A	88 A	78 A	68 A
I_3 (Dry)	160 A	111 A	92 A	83 A	75 A

1/ Mean of seventy-two counting plots (four replications times two planting depths times three row cover treatments times three irrigation levels.

* Means followed by the same letter are not significantly different at the 5% level.



12 GUAYULE CONDITIONED SEED ROWS
46 SEEDS/M (14 SEED/ft), 64 COUNTING PLOTS

8 ROW COVER TREATMENTS

A. CHECK
B. FIRST WHEAT PLANTING
C. SECOND WHEAT PLANTING
D. AGRONET (10% SHADE)
E. REEMAY (20% SHADE)
F. POLYSHADE CLOTH (40% SHADE)
G. POLYSHADE STRIPS (40% SHADE)
H. AMERICAN STRAW MAT
I. GREENHOUSE STARTED TRANSPLANTS

WCL = WATER CONSERVATION LABORATORY GREENHOUSE PLANTS.
CRC = CHECK = COTTON RESEARCH CENTER GREENHOUSE PLANTS
CRC, CO_2 = COTTON RESEARCH CENTER GREENHOUSE PLANTS, CO_2 ENRICHED ENVIRONMENT

3 PLANTING METHODS.

FI - FLUID DRILLING AT SOIL SURFACE (IMBIBED, CONDITIONED)
FNI - FLUID DRILLING AT SOIL SURFACE (NONIMBIBED, CONDITIONED)
PP - PRECISION PLANTED AT 0-5mm SOIL DEPTH (NONIMBIBED, CONDITIONED)

Fig. 1. Field diagram showing eight row cover crops, three planting methods, and an area designated I, used initially as a weather station site and then as a plot for greenhouse grown transplants.

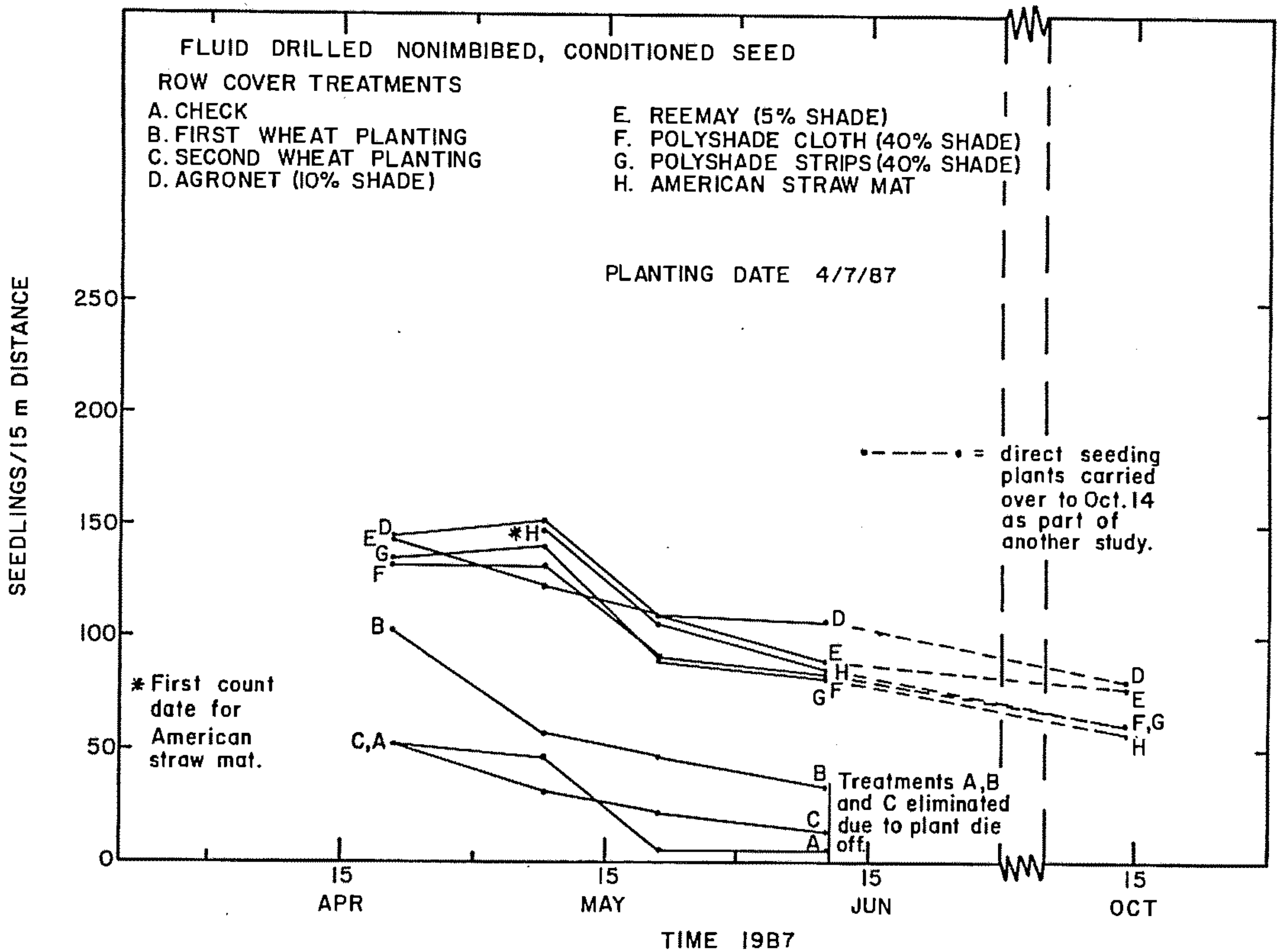


Fig. 2. Guayule seedling counts per 15 meter distances versus time for eight selected row cover treatments using fluid drilled, nonimbibed, conditioned seed in the Summer and Fall 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

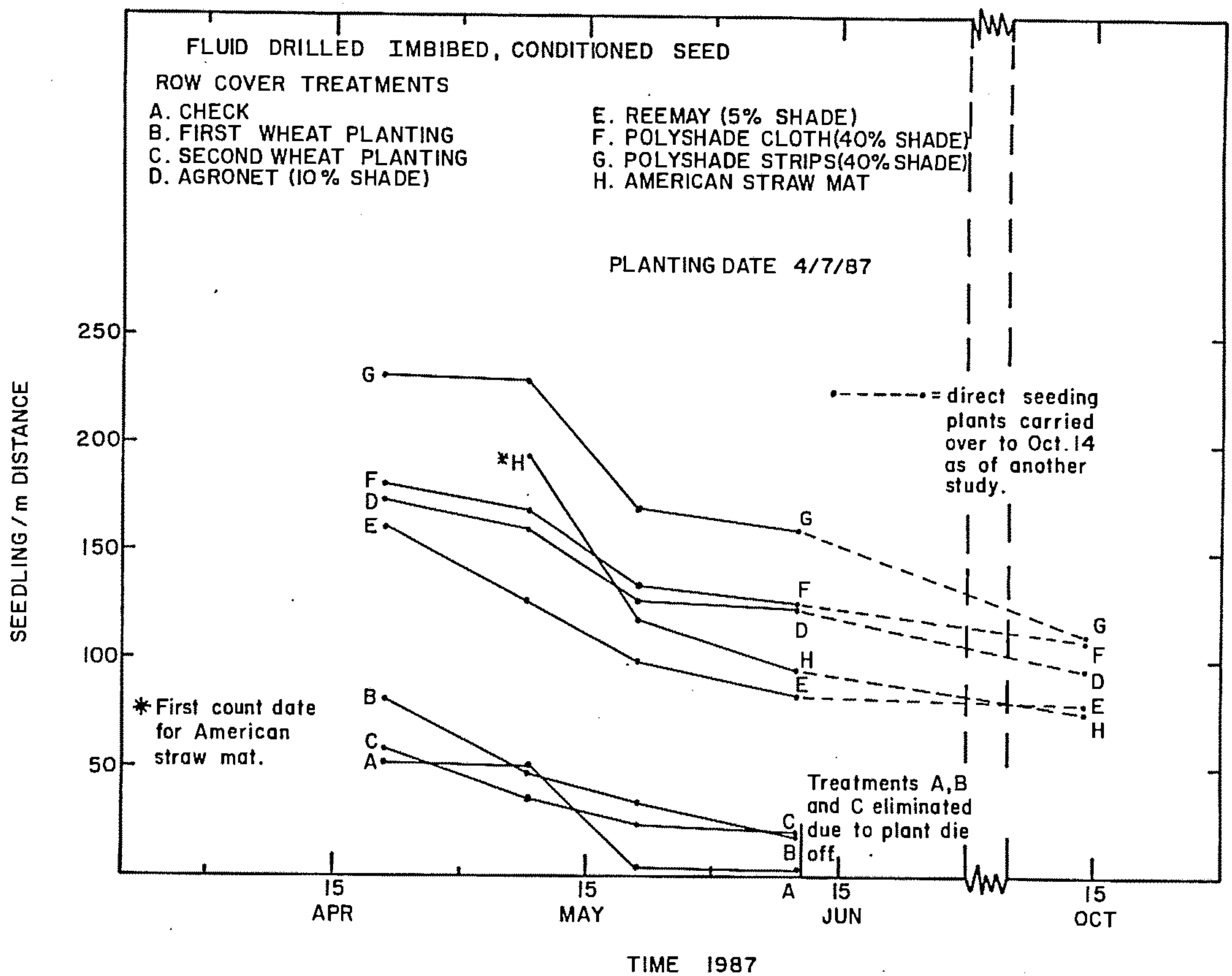


Fig. 3. Guayule seedling counts per 15 meter distances versus time for eight selected row cover treatments using fluid drilled, imbibed, conditioned seed in the Summer and Fall 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

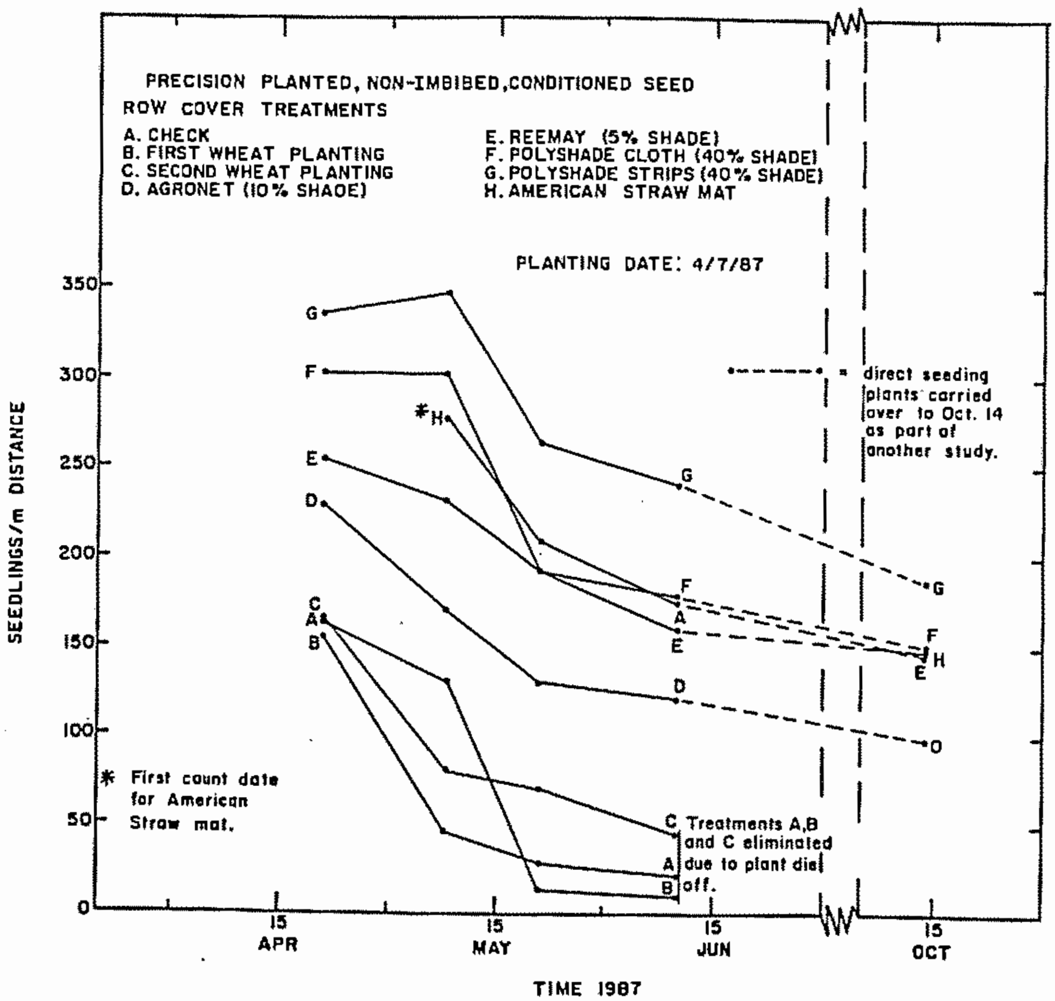


Fig. 4. Guayule seedling counts per 15 meter distances versus time for eight selected row cover treatments precision planted, using nonimbibed, conditioned seed in the Summer and Fall 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

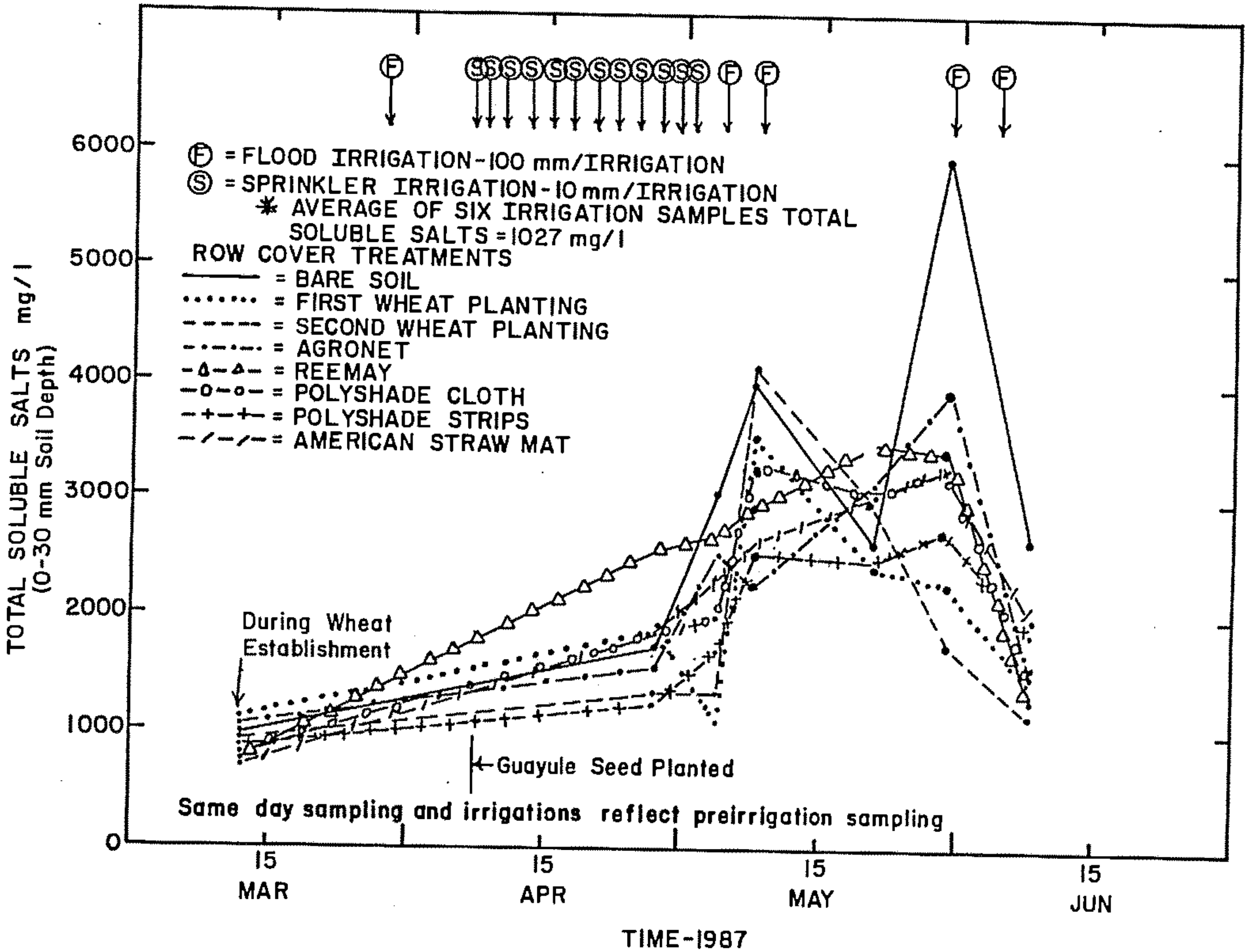


Fig. 5. Total soluble salts for eight row cover treatments in the Spring 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

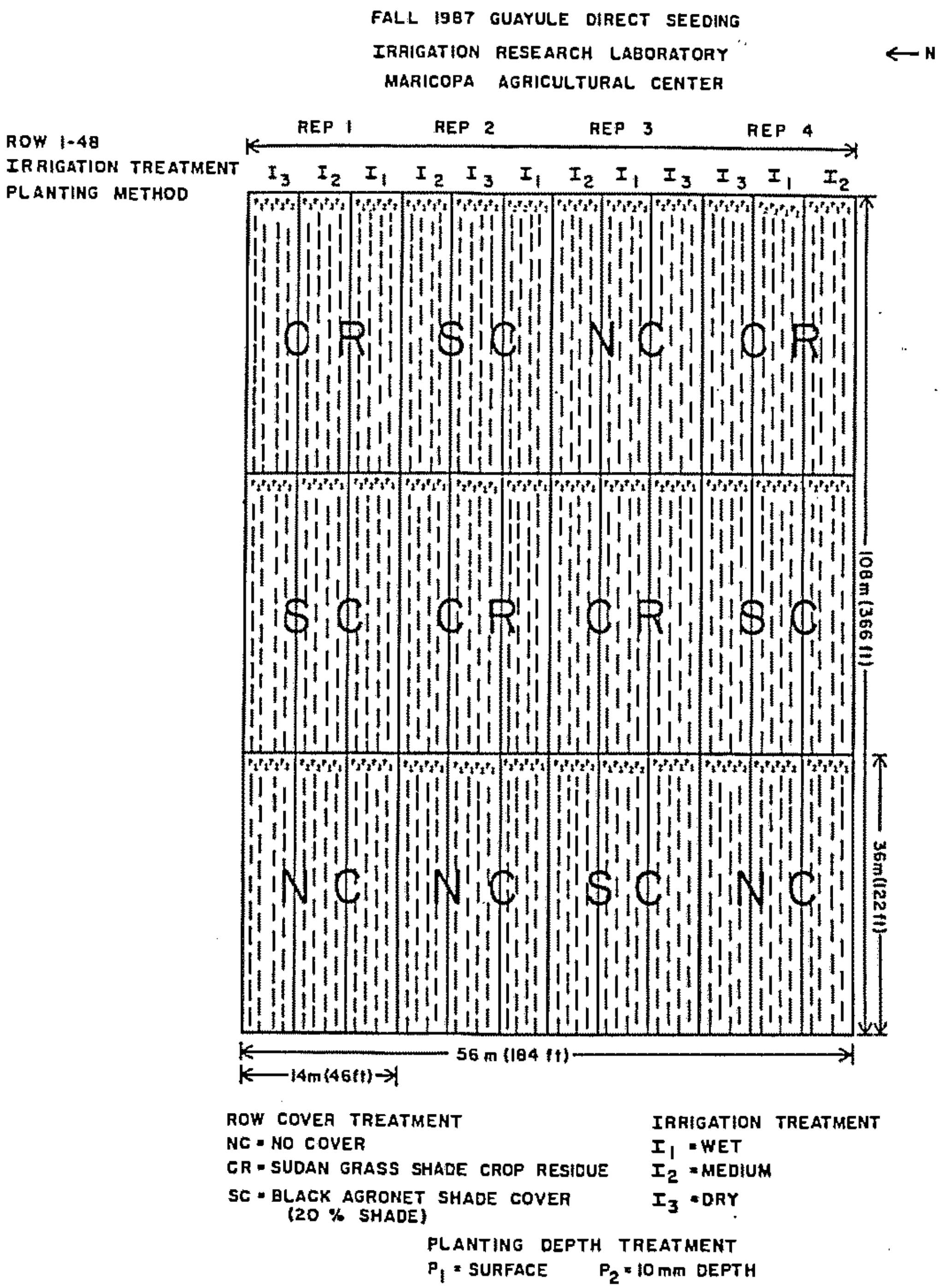


Fig. 6. Field plot plan for Fall 1987 direct seeding experiment, Maricopa Agricultural Center, Maricopa, Arizona.

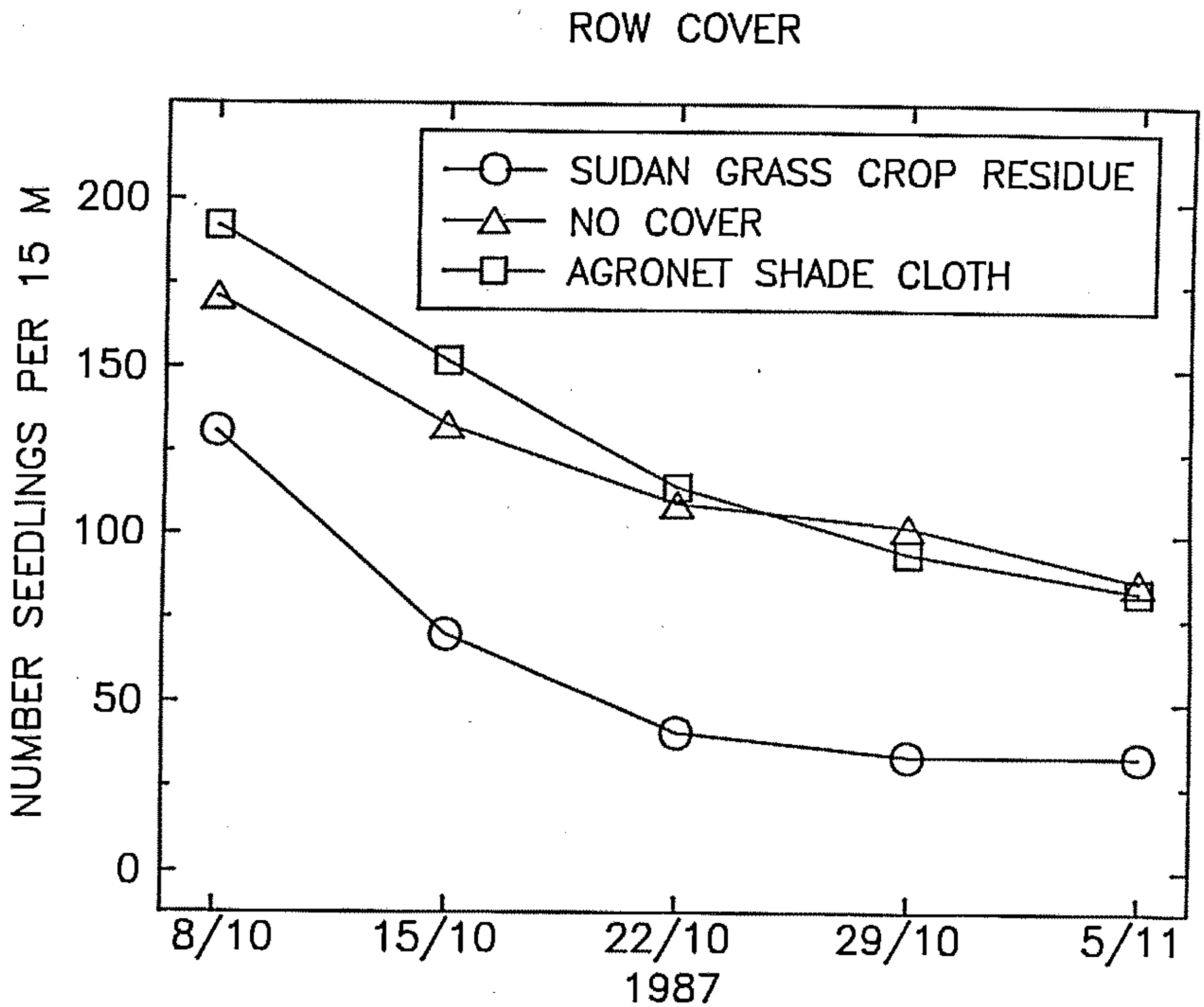


Fig. 7. Guayule seedling counts per 15 meter distances versus time with three row cover treatments using conditioned seed in the Fall of 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

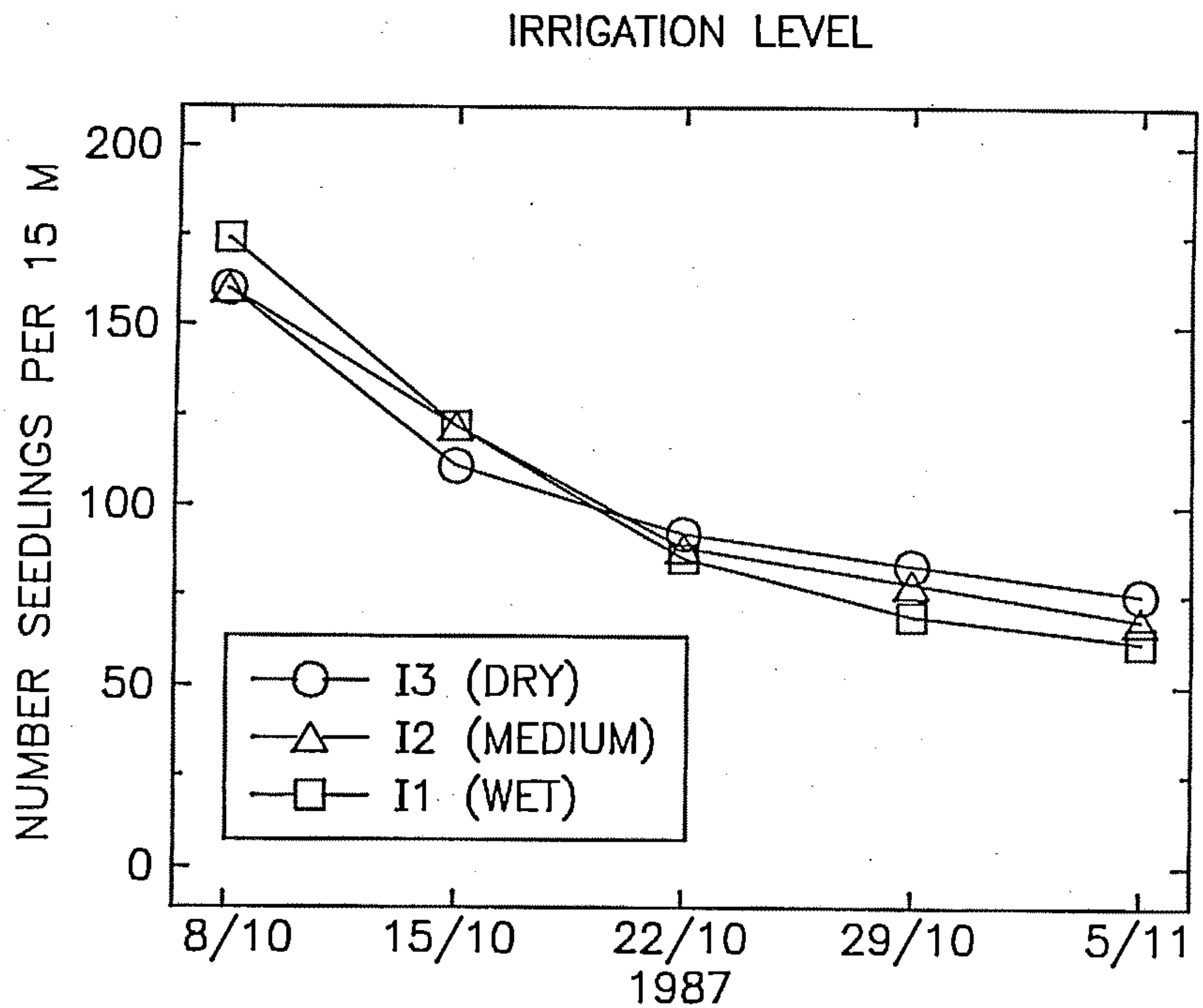


Fig. 8. Guayule seedling counts per 15 meter distances versus time with three irrigation levels using conditioned seed in the Fall of 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

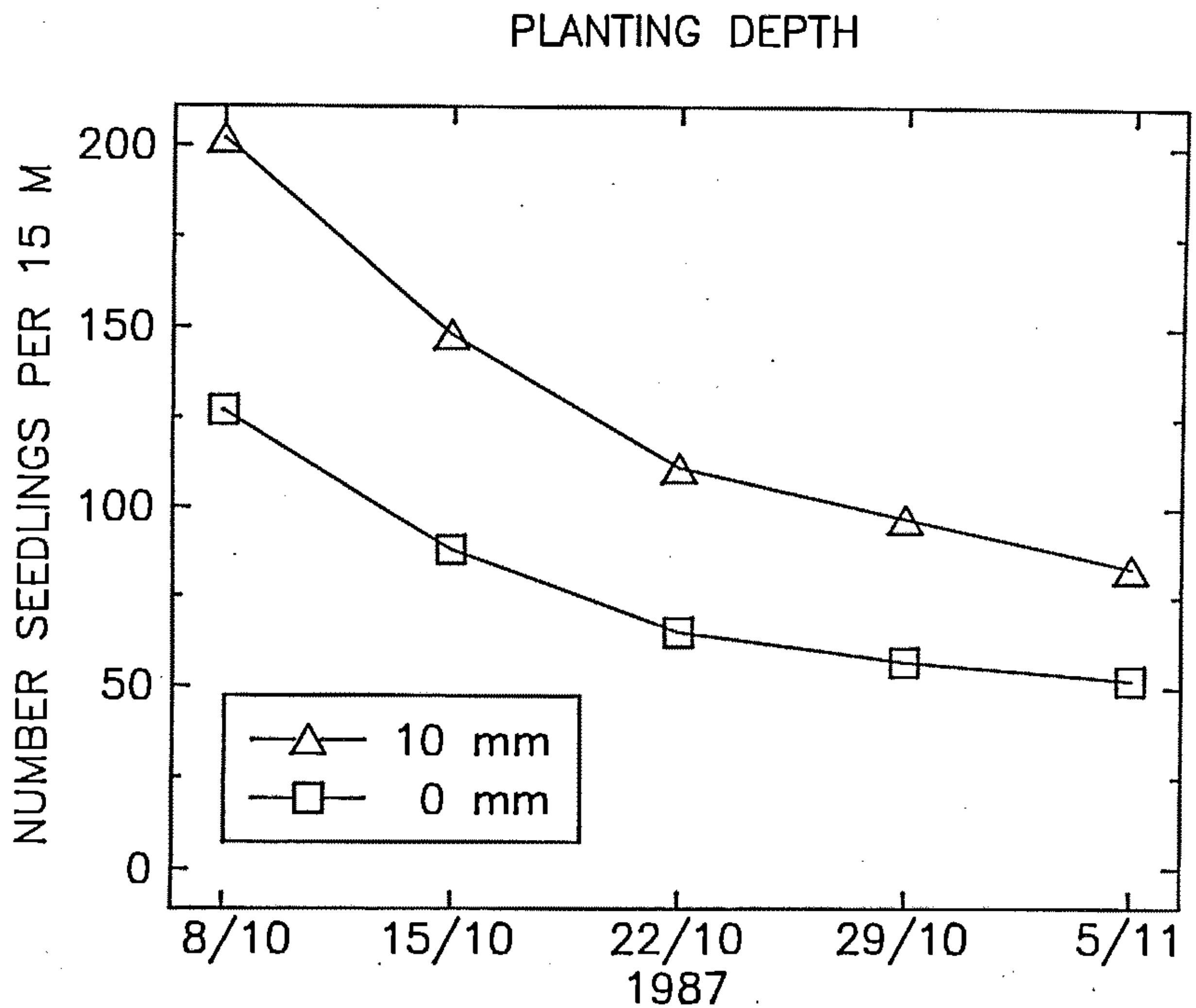


Fig. 9. Guayule seedling counts per 15 meter distances versus time with two planting depths in the Fall of 1987 at the Maricopa Agricultural Center, Maricopa, Arizona.

TITLE: EFFECT OF MANUAL DEFLOWERING ON RUBBER CONTENT AND BIOMASS OF GUAYULE

SPC: 2.3.04.1.p CRIS WORK UNIT: 5344-13230-001

INTRODUCTION

During 1986 a small-scale, preliminary experiment was conducted to examine the effects of manual deflowering on guayule rubber, resin, and biomass yield. The study was based on the hypothesis that photosynthate normally routed to the production of reproductive structures and processes might become available for growth and rubber production if the flowers were continuously removed during the growing season. Such a hypothesis is supported by another experiment in which deflowering of guayule had a beneficial effect on rubber yield (Willard, 1986).

MATERIALS AND METHODS:

This experiment was conducted using the outside border rows of another guayule experiment conducted during 1986 at the Maricopa Agricultural Center. The field layout and experiemental design are described in detail in the 1986 Annual Report. In brief, six outside border rows were used in this study. Three of the rows were deflowered by hand, by removing flowers from the end of the peduncles, once or twice a week, as necessary, from the beginning of the flowering period in the spring of 1985 through January of 1986. The remaining rows served as a check. Three plants from each row were harvested in January 1986 and analyzed for biomass, rubber content, and main-stem diameter at ground level.

RESULTS

Table 1 shows the effects of deflowering on rubber content, plant biomass, and stem diameter. The deflowering processes significantly increased all three factors compared to the control plants. Rubber percent and biomass were 9 and 29% greater in the deflowered plants than the check plants. When these two factors are multiplied, the deflowered plants were found to have 36% more rubber per plant than the checks.

Although these results are only preliminary, it appears that there may be substantial benefit from deflowering of guayule, but only if an inexpensive and effective means can be found to cause the deflowering. This study warrants further research to find either chemical or mechanical means to cause deflowering of guayule.

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PERSONNEL

S. G. Allen and F. S. Nakayama

Table 1. Effect of Manual Deflowering of Guayule During the First Year of Growth.

Treatment	Percent Rubber	Plant Biomass (g)	Stem Diameter (cm)
Control	3.75 a	340 a	1.92 a
Deflowered	4.14 b	481 b	2.21 b

Means followed by different letters are significantly different at 0.05 level by LSD.

TITLE: RELATIONSHIP BETWEEN CROP WATER STRESS INDEX AND OTHER PLANT WATER STATUS INDICATORS IN GUAYULE

SPC: 2.3.04.1.n 20%
1.3.03.1.d 80%

Cris Work Unit: 5344-13230-001

INTRODUCTION

Guayule (Parthenium argentatum Gray) is a xerophytic rubber producing shrub capable of surviving in its native habitat of northern Mexico and the southwestern United States with as little a 175 to 380 mm of rainfall per year (Ray, 1983). Guayule has been shown to be very tolerant of desiccation (Ehrler *et al.*, 1985; Ehrler and Nakayama, 1984) and to undergo osmotic adjustment in response to soil moisture stress (Allen *et al.*, 1987).

Guayule rubber yield is affected in two apparently opposing ways by soil moisture stress. Bucks et al. (1985) have shown that guayule dry matter, rubber and resin yields are linearly related to the amount of irrigation water applied, with the greatest amounts of water producing the highest yields. Other studies, however, indicate that soil moisture stress causes guayule to accumulate a greater percentage of rubber in its roots and stems (Retzer and Mogen, 1947; Veihmeyer and Hendrickson, 1961; Hammond and Polhamus, 1965; Mondrus-Engle and Younger, 1983). This inverse relationship between plant growth and rubber content suggests that precise water management and the determination of plant water status of guayule may be critical for maximum economical production.

Plant temperatures have long been recognized as a potential indicator of soil moisture availability (Gates, 1964; Wiegand and Namken, 1966; Aston and van Bavel, 1972; Ehrler, 1973; Idso and Ehrler, 1976; Jackson *et al.*, 1977; Byrne *et al.*, 1979; Jackson, 1982) and plant water status (Tanner, 1963; Ehrler *et al.*, 1978a, b; Idso *et al.*, 1978). The crop water stress index (CWSI) provides a quantitative measure of plant water status based on the foliage-air temperature differential (Tc-Ta) as a function of the vapor pressure deficit (VPD) of the atmosphere (Idso, *et al.*, 1981; Jackson *et al.*, 1981). Nakayama and Bucks (1983; 1984) applied the CWSI to guayule and found a significant relationship between the seasonally averaged CWSI and rubber yield.

In this report, we examine the relationship between the CWSI and several other physiological indicators of plant water status of guayule during a prolonged drought period. A technique for improving the precision of CWSI measurement and potential problems encountered using the CWSI with guayule are also discussed.

MATERIALS AND METHODS

Ten-week-old greenhouse-propagated guayule seedlings (cv. N565 II) were transplanted on 22 March 1986 into field plots at Phoenix, AZ, where the soil type was an Avondale loam (a fine, loamy, mixed calcareous, hyperthermic, Antropic Torrifluvent). All plots were fertilized with 57 kg N ha^{-1} as $Ca(NO_3)_2$ prior to planting.

The field plots consisted of two replications of two soil moisture level treatments, one representing well-watered (wet) and the other water-stressed (dry) conditions. Each plot consisted of five beds with eight plants per bed. The wet treatment was irrigated at approximately 10-day intervals throughout the experiment such that the available soil moisture content in the root zone remained above 70%. The dry treatment received no irrigations between 29 May and 5 August 1986. During this period the available soil moisture content declined from 100 to 0%. The dry plots were irrigated again on 5 August so that the soil moisture content reached field capacity. Both treatments were irrigated with a micro-irrigation system (T-tape type C, T-Systems, Corp., San Diego, CA). Volumetric soil moisture content to a depth of 2.2 m was determined two to three times each week during the experiment using2a neutron moisture meter (model 503, Campbell Pacific Nuclear Corp., Pacheco, CA) previously calibrated in the same soil type. Detailed descriptions of seedling propagation methods and the field site are provided in Allen *et al.* (1987).

Pyschrometric measurement of leaf water potential (Ψ_L), osmotic potential (Ψ_S), and turgor potential (Ψ_P), canopy net photosynthesis (Pn), and porometer measurements of transpiration (Tr) and stomatal conductance (Cs) were conducted between 1000 and 1045 hr local time two to three times per week, on cloudless days, between 12 June and 16 August as previously described (Allen *et al.*, 1987). Crop water stress index (CWSI) was measured concurrently with the other physiological measurements as described by Idso *et al.* (1981). The nonwater-stressed baseline used in calculating CWSI was constructed from several diurnal measurements (19 and 27 June and 23 July 1986) of vapor pressure deficit (VPD) and Tc - Ta using the well-watered plants. Foliage temperatures of individual plants (12 per plot) were measured with an infrared thermometer (model 110, Everest Interscience, Tustin, CA) with an 8° field of view. VPD was calculated from wet and dry bulb temperatures measured with an aspirated psychrometer (model 566, Bendix Corp., Baltimore, MD).

RESULTS

The CWSI values of the plants in the dry and wet treatments, as calculated for the period between 12 June and 16 August 1986, are shown in Fig. 1a. At the beginning of this period the CWSI values for the two treatments were nearly identical. However, as the soil moisture content in the dry plots began to decline, the CWSI values of the dry plants gradually increased above those of the wet plants. On 5 August the dry plots were irrigated again to relieve the stress, and the difference in CWSI between the dry and wet treatments decreased.

A great deal of day to day variation in CWSI can also be seen in Fig. 1a. This variation obscures the relationship between the wet and dry treatments. The primary reason for this temporal variation is that the CWSI was calculated using the empirical approach of Idso et al. (1981) which does not fully take into account environmental factors, such as wind speed, which may influence the Tc - Ta differential. In order to remove this variation, the data were normalized by subtracting the mean wet treatment CWSI values from those of the dry treatment as shown in Fig. 1b. The hand-drawn lines in Fig. 1b show more clearly the progressive difference in CWSI between the wet and dry plots as the length of the drought treatment increased, as well as the partial recovery from stress following irrigation of the dry plots on 6 August. The mean results for the other parameters measured during the experiment were normalized in a similar manner to examine their relationship with the normalized CWSI data.

A significant linear relationship ($r^2 = 0.70$, $P < 0.01$) between the normalized CWSI and normalized percent available soil moisture content up until the dry plots were irrigated on 6 August. The solid circles in Fig. 2 represent data collected during the 11-day period following the irrigation. Although the soil moisture contents of the two treatments were nearly the same following irrigation, the CWSI values of the dry plants remained between 0.3 to 0.5 units higher than those of the wet plants.

The physiological parameters that were most closely correlated with CWSI were Ψ_L (Fig. 3, $r^2 = 0.75$, $P < 0.01$) and Ψ_S (Fig. 4, $r^2 = 0.70$, $P < 0.01$). The linear regressions of both of these relationships extended very close to the point $x = 0$, $y = 0$ such that the initial differences among the irrigation treatments for CWSI and Ψ_L and Ψ_S were detected at approximately the same time. This result indicates a similar sensitivity to changes in plant water status for CWSI, Ψ_L and Ψ_S.

A much different result was found for the relationship between CWSI and Ψ_P (Fig. 5). There was no apparent difference in Ψ_P between the wet and dry treatments with increasing difference in CWSI until their difference in CWSI reached approximately 0.55. Allen et al. (1987) have shown that guayule exhibits a significant amount of osmotic adjustment which results in turgor maintenance during drought stress. This critical normalized CWSI value of 0.55 represent a threshold beyond which the dry-treated plants were no longer able to maintain turgor equal to the well-watered plants through osmotic adjustment.

The normalized Tr (Fig. 6) and Cs (Fig. 7) data both resulted in significant ($P < 0.01$) linear relationships with the normalized CWSI data ($r^2 = 0.58$ and 0.62, respectively).

There was no statistically significant relationship between normalized CWSI and Pn (Fig. 8). Although the plants in the dry treatment attained CWSI values as much as 0.8 units greater than those in the wet treatment, there was essentially no difference in Pn rates between the two treatments. Pn rates in both treatments were low, however, with a mean rate of approximately 6 μmol CO_2 m^{-2} s^{-1}. Therefore, partial stomatal closure of plants in the dry treatment due to moisture stress (Fig. 7), did not reduce the CO_2 concentration within the leaf to a level that restricted Pn.

DISCUSSION

A close agreement was observed for the relationships between the normalized CWSI and the knormalized values of the physiological parameters, Ψ_L, Ψ_S, Tr and Cs, traditionally used as indicators of plant water status. This close relationship was not as close, however, when the non-normalized values of CWSI were regressed upon the non-normalized values of the physiological parameters (Table 1). For example, whereas the linear relationship between the non-normalized CWSI and Ψ_L values for the dry treatment resulted in $r^2 = 0.45$.

The primary cause of the lower correlations between non-normalized values of CWSI and the other physiological parameters was the temporal variation in CWSI values related to changes in environmental conditions. Previous studies of the applicability of the CWSI as an indicator of water stress in guayule have also reported substantial temporal variability in CWSI values not related to soil moisture availability (Nakayama and Bucks, 1983 and 1984). These studies also used the empirical method of Idso et al. (1981) to calculate CWSI. Other studies have shown that the precision of the CWSI can be improved if the effects of other environmental factors are considered when relating the Tc - Ta differential to VPD (Jackson et al., 1981; Smith et al., 1986).

In the present experiment, normalizing the CWSI successfully removed some of the variability due to environment. For practical use of the CWSI to monitor plant water status in the field, it may be simpler for the user to maintain a well-watered plot for this purpose, as suggested by Clawson et al. (unpublished data), than to measure all of the environmental factors necessary to correct the CWSI using a complete energy budget approach.

The CWSI of the plants in the dry treatment remained 0.3 to 0.5 units higher than the well-watered plants during the 11-day period following the 5 August 1987 irrigation of the water-stressed plants (Fig. 1b and 2), although the difference in CWSI between the two treatments appeared to be declining during this period. A delay in recovery of leaf temperature and CWSI to control levels following removal of soil moisture stress has been observed with cotton (Ehrler, 1973), sorghum (Idso and Ehrler, 1976) and wheat (Jackson, 1982), although the CWSI of these crops returned to those of their well-watered counterparts within three to six days following removal of the water stress. Due to the much longer lag period noted for guayule (greater than eleven days), care must be taken to avoid overestimating soil moisture stress during this period.

Jackson (1982) believed that a five to six day delay in recovery of CWSI of water-stressed wheat plants following irrigation was related to the time necessary for leaves to rehydrate and for the development of root hairs on roots previously contained in dry soil. In the present experiment, morphological changes to the aerial portion of the water-stressed plants may also have contributed to the apparent delayed recovery from water stress. The leaves of the water-stressed guayule plants were noticeably thicker and more densely covered with trichomes than the well-watered plants as evidenced by their silvery color (Ray, 1983; Hammond and Polhamus, 1965; Lloyd, 1911). The water-stressed plants also carried a larger proportion of nontranspiring senesced leaves than the well-watered plants. These conditions reduced transpiration and increased leaf temperature. These altered morphological characteristics caused the CWSI values to be greater than those of the well-watered plants even though the soil moisture contents were similar in both treatments, indicating that the nonwater-stressed baseline developed for the well-watered plants no longer applied to the water-stress-treated plants. Therefore, part of the observed recovery of guayule CWSI following irrigation is the development of new leaves with a morphology characteristic of well-watered plants.

CONCLUSION

The normalization of the CWSI data successfully removed environmental effects on the index and provided better correlations between CWSI and traditional plant water stress indicators than did the non-normalized values. Significant linear relationships were established between the normalized CWSI and normalized values of $_L$, Ψ_S, Tr, and Cs. Ψ_P of the plants in both treatments were similar until their difference reached a threshold value of approximately 0.55, beyond which the water-stressed plants were no longer to maintain turgor though osmotic adjustment. No difference in Pn was observed between the wet and dry plots even though their difference in CWSI was as agreat as 0.80. During an 11-day period following irrigation of the water-stressed plants their CWSI values remained significantly higher than the well-watered plants even though the soil moisture contents of the two treatments were similar.

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PERSONNEL

S. G. Allen and F. S. Nakayama

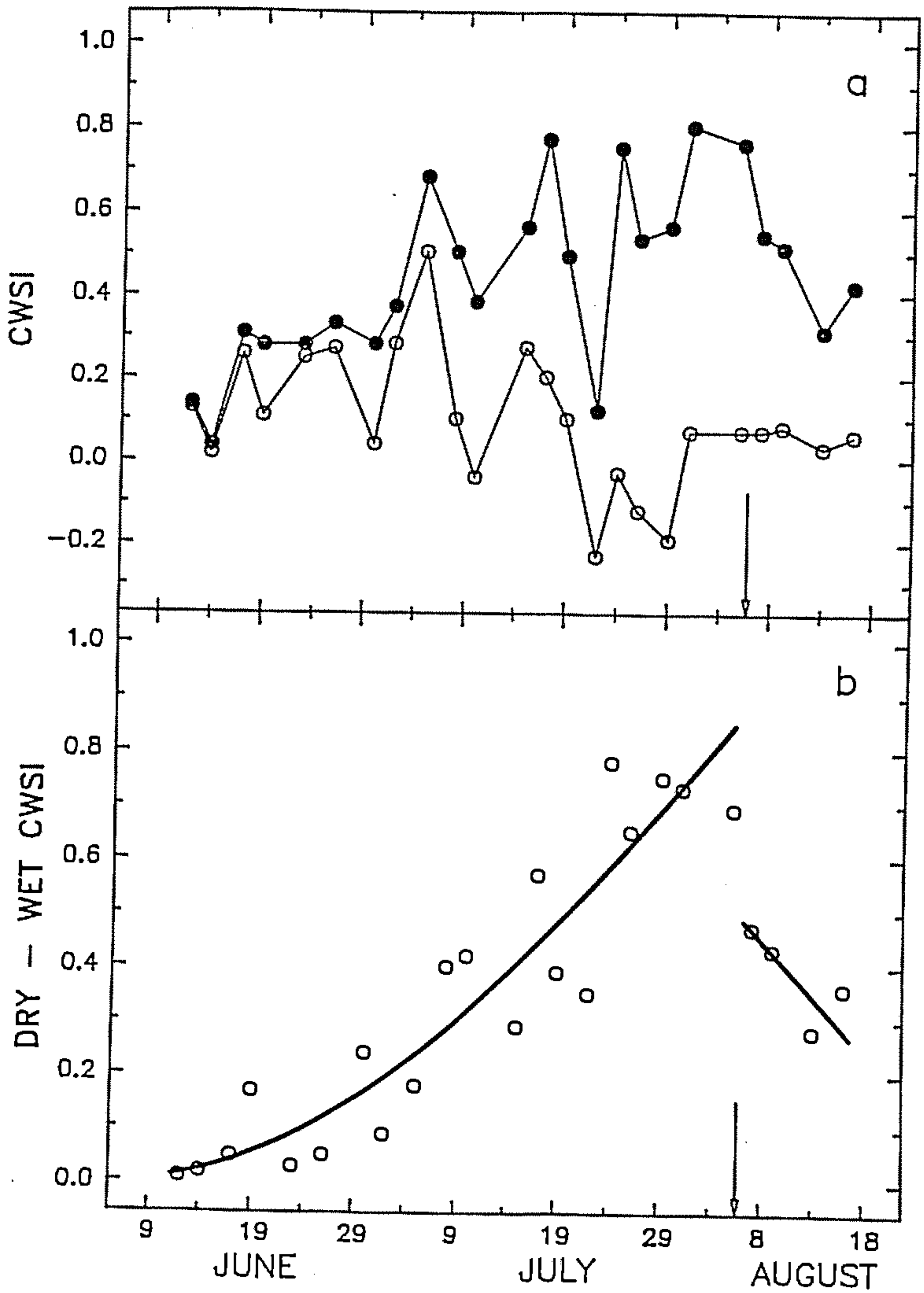

Fig. 1. (a) Crop water stress index (CWSI) of well-watered (open circles) and water-stressed (solid circles) guayule and (b) normalized CWSI between 12 June and 16 August 1986. Arrows on x-axis indicate date (5 August) on which the 70-day drought treatment of the water-stressed plants was ended.

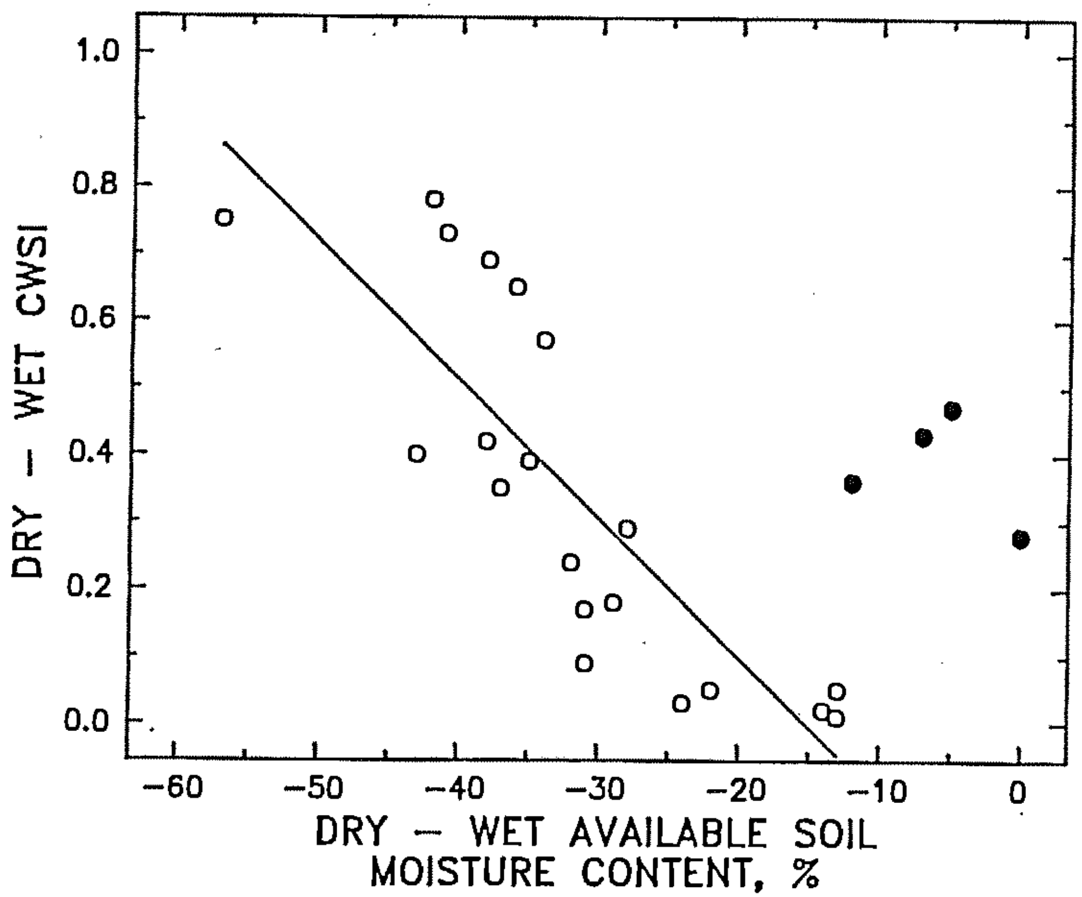

Fig. 2. Linear relationship between normalized crop water stress index (CWSI) and normalized available soil moisture content. The solid circles represent data collected during the 11-day period following irrigation of the water-stressed plants on 5 August 1986. For open points $r^2 = 0.70$, $P < 0.01$, $n = 20$.

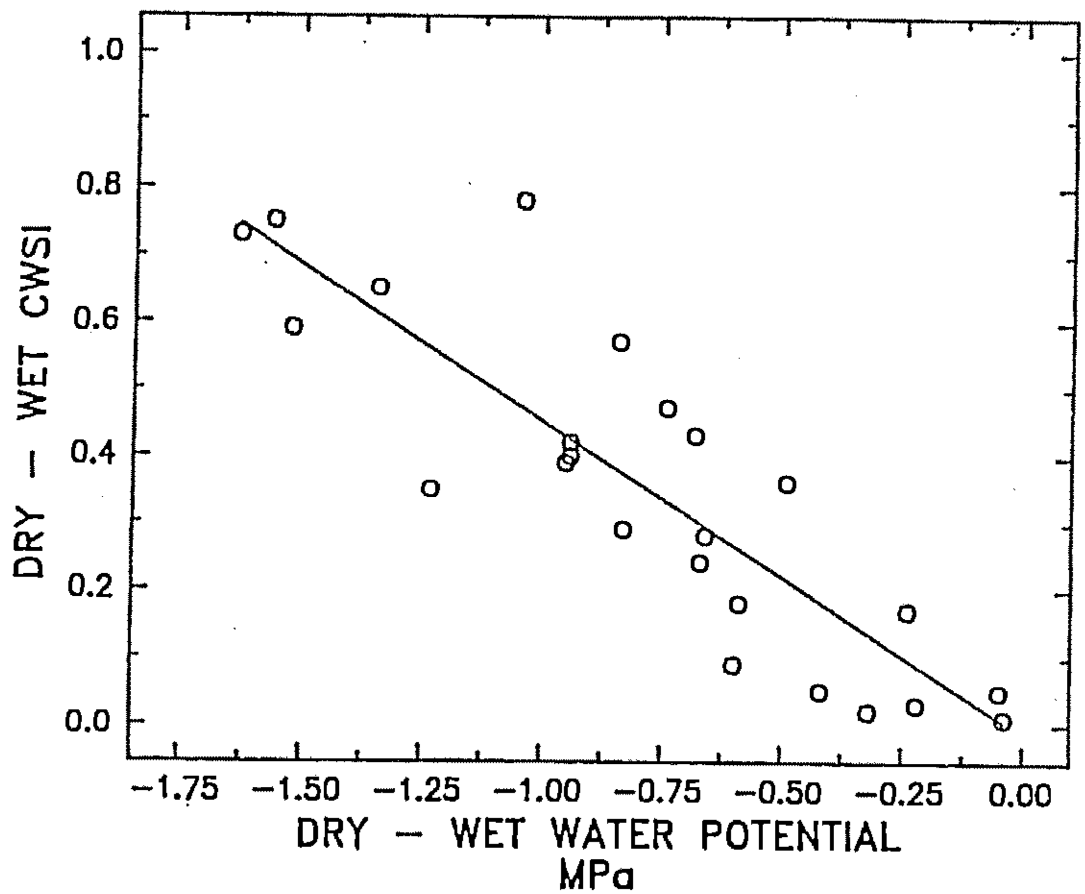

Fig. 3. Linear relationship between normalized crop water stress index (CWSI) and normalized leaf water potential (Ψ_L) of guayule. $r^2 = 0.75$, $P < 0.01$, $n = 24$.

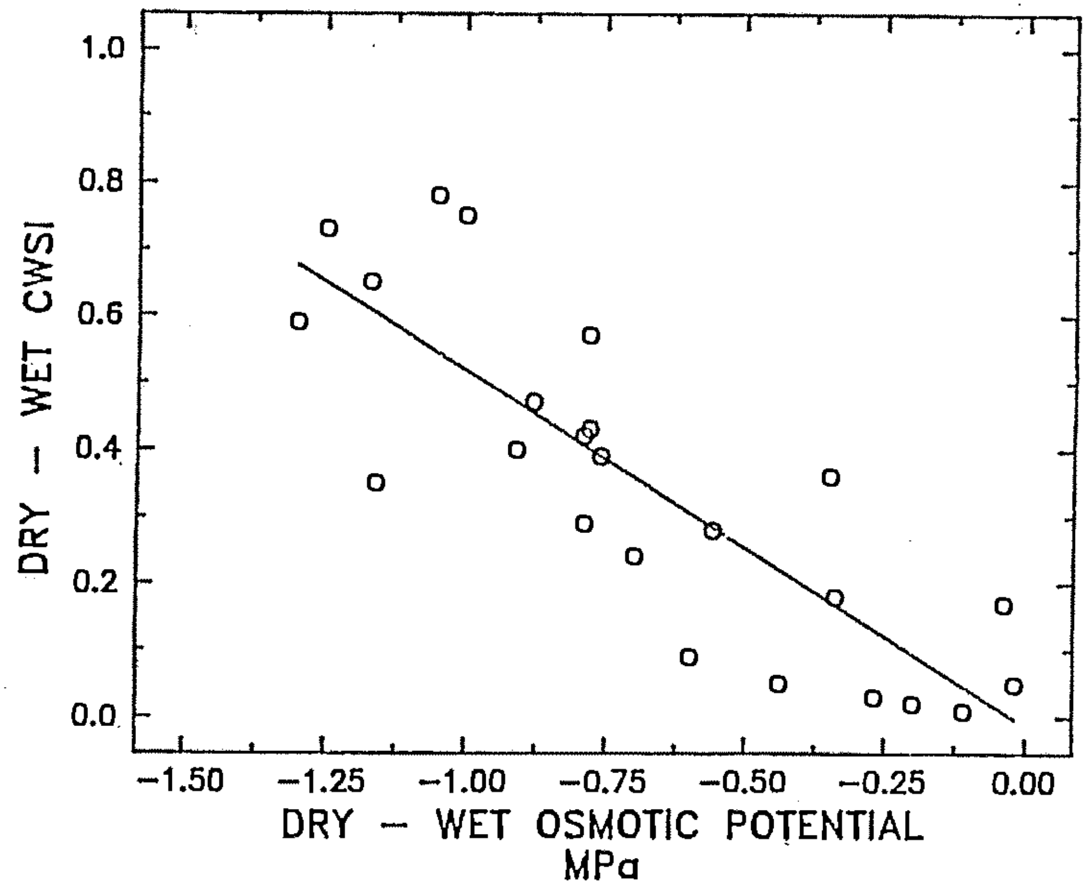

Fig. 4. Linear relationship between normalized crop water stress index (CWSI) and normalized leaf osmotic potential (Ψ_S) of guayule. $r^2 = 0.70$, $P < 0.01$, $n = 24$.

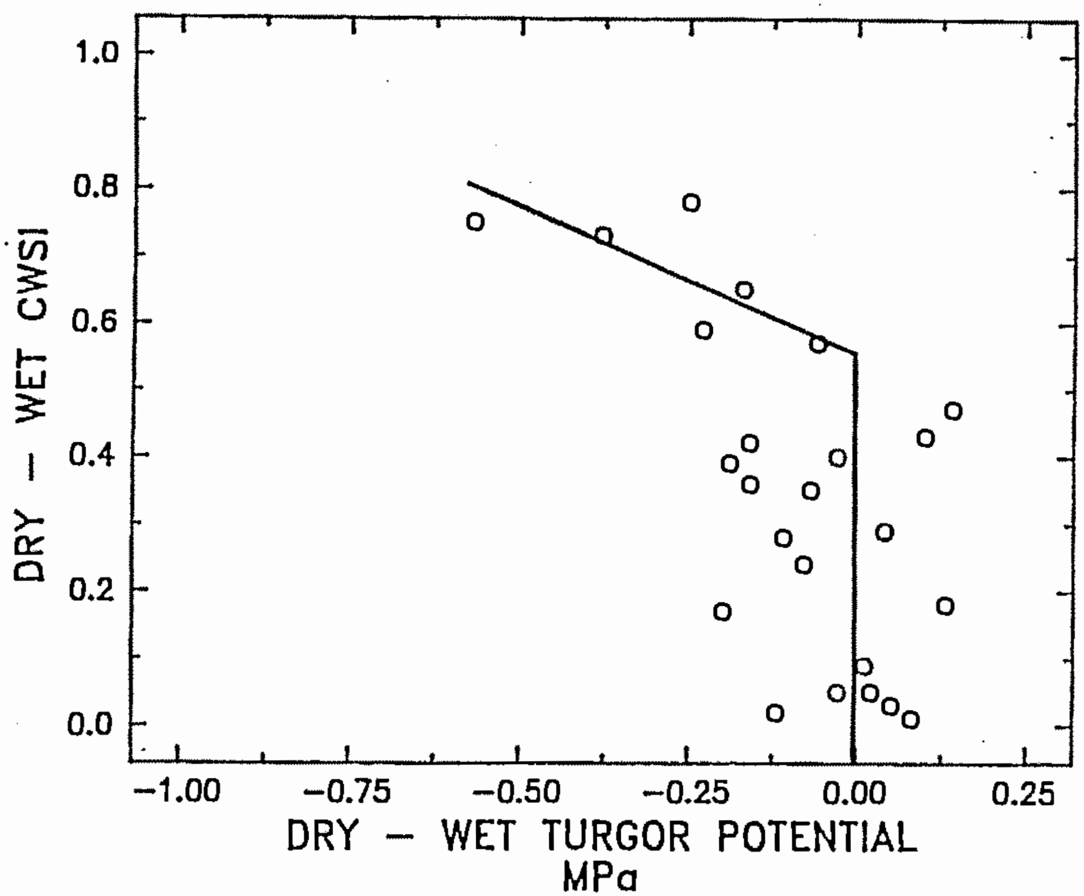

Fig. 5. Relationship between normalized crop water stress index (CWSI) and leaf turgor potential (Ψ_p) of guayule.

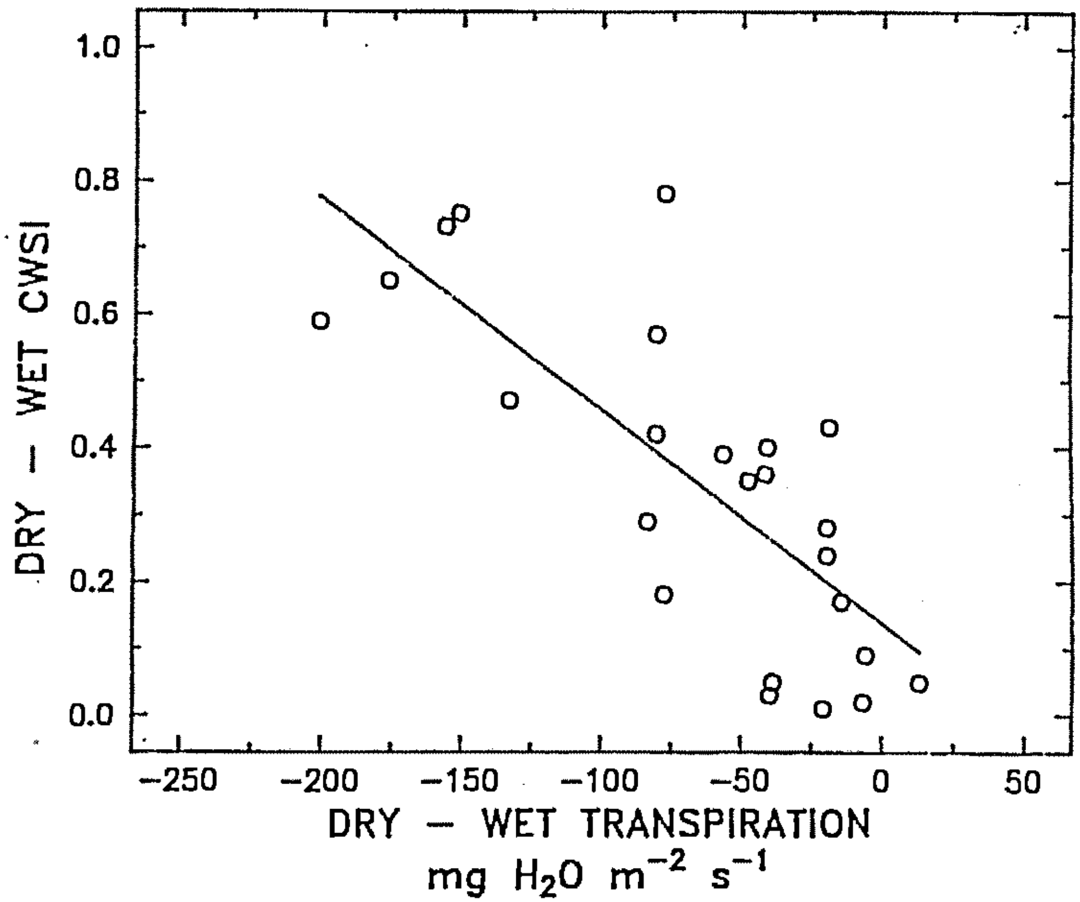

Fig. 6. Linear relationship between normalized crop water stress index (CWSI) and transpiration (Tr) of guayule. $r^2 = 0.58$, $P < 0.01$, $n = 24$.

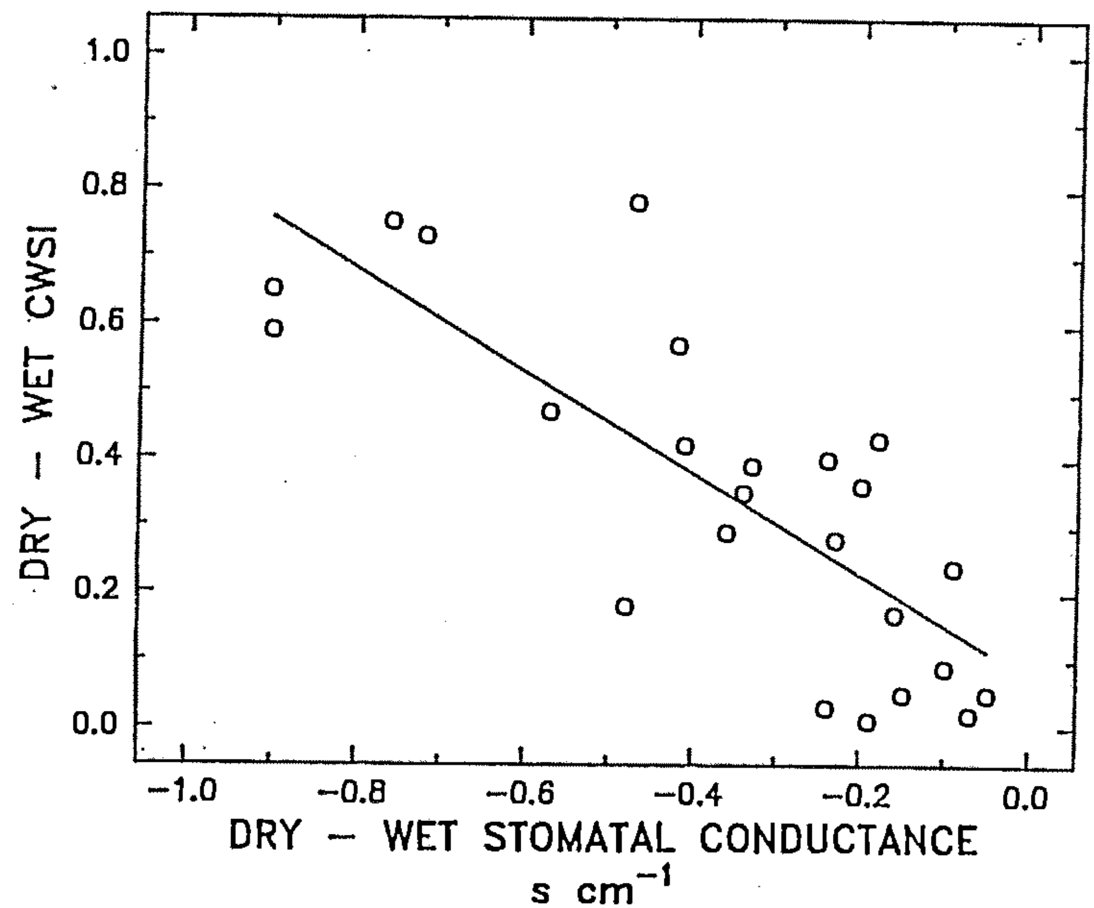

Fig. 7. Linear relationship between normalized crop water stress index (CWSI) and stomatal conductance (Cs) of guayule. $r^2 = 0.62$, $P < 0.01$, $n = 24$.

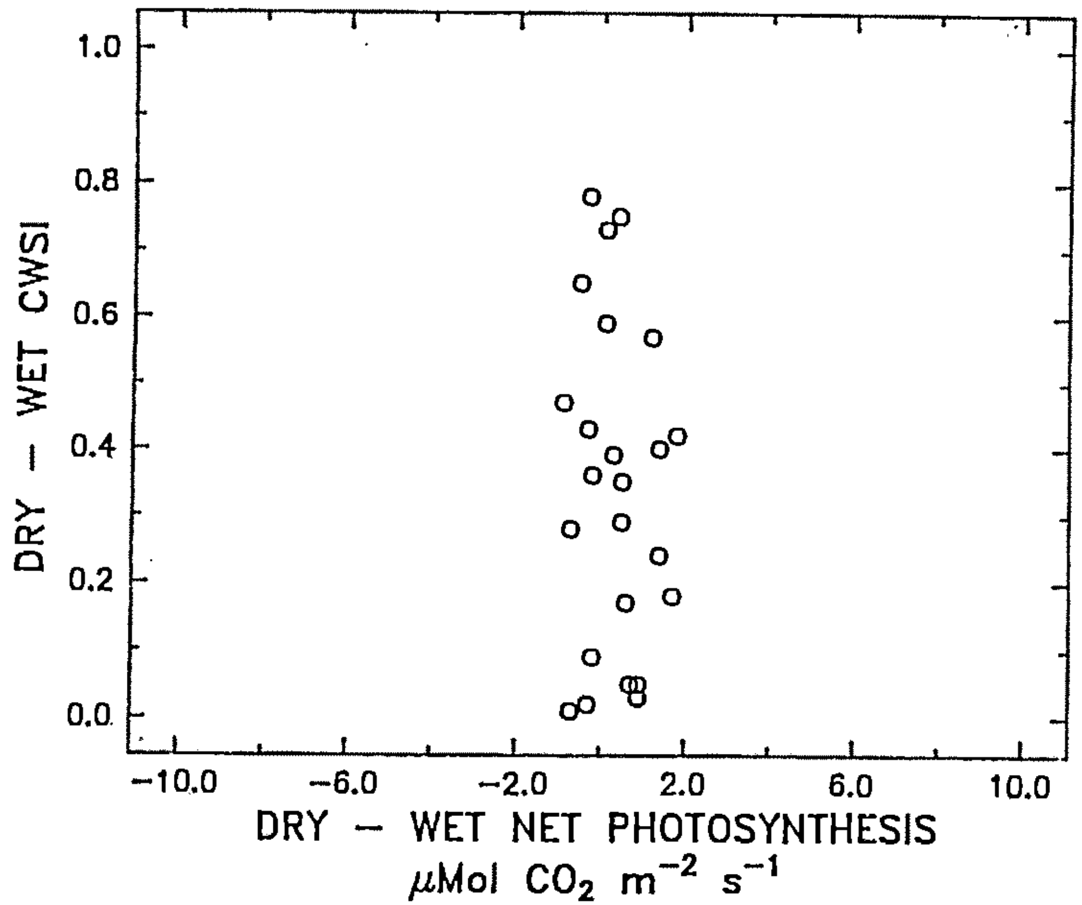

Fig. 8. Relationship between normalized crop water stress index (CWSI) and net photosynthesis (Pn) of guayule.

TITLE: SURFACE SOIL WATER CONTENT DETERMINATION WITH THE NEUTRON PROBE

SPC: 1.3.03.1.d 80%
2.3.04.1.N 20%

CRIS WORK UNIT: 5344-13230-001

INTRODUCTION

An adequate supply of soil water near the seed is important for its successful germination and consequent plant establishment. The slow-growing guayule seedling is extremely susceptible to slight changes in the environment and its survival is highly dependent upon proper water and salinity conditions. Determination of soil water content near the soil surface, where guayule and other types of seeds are placed, is usually made by gravimetric sampling. This procedure is extremely time labor intensive and time consuming, and also can disturb the seed and seed bed. To avoid this, surface neutron moisture equipment can be adapted to determine the seed-bed water content in an non-destructive manner. Our earlier work with the neutron surface probe (Farah, Reginato and Nakayama, 1984) discussed the calibration process and test of the equipment, but did not extend its use to actual field applications, This report covers the results obtained from field trials in conjunction with an experiment for studying the effects of various factors, including soil water content, on guayule plant establishment by direct seeding.

PROCEDURE

The neutron surface probe equipment (Campbell-Pacific Model MC-M Roof Gauge) was calibrated on the Casa Grande sandy loam soil where the guayule direct seeding experiments were being conducted. The soil sampling and neutron reading procedures were essentially those reported earlier (Farah, Reginato, and Nakayama, 1984). Since we were interested only in the very shallow depths, soil samples were taken over the 0- to 2-cm, 0- to 5-cm, and the 0- to 8-cm increments.

A 1.8 mm (15 gauge) cadmium sheet was used to fabricate a cover over the neutron probe to cut down the extraneous readings caused by surrounding fast neutron moderators.

For the field trials, 16 plots were selected for the neutron readings. The soil was leveled and the site marked so that the probe could be set at the same spot for the repeated readings to be made over the progress of the experiment to follow soil water changes as a result of irrigation, rainfall, and evapotranspiration. Equipment readings were taken at the same time that the seed bed was sampled manually for water content with a soil moisture sampling probe.

RESULTS AND DISCUSSION

The calibration values for the surface neutron probe for the various depth increments are as follows:

Table 1. Parameters for field calibrated surface probe at the various soil depth increments.

Depth Increment (cm)	Intercept	Slope	r^{-2}
0- to 2	-17.91	78.86	0.94
0- to 5	-11.32	69.87	.98
0- to 8	- 1.58	51.09	.99

The linear regression equation fitted the experimental points, with correlation coefficients of better than 0.9.

Comparison of the gravimetric and neutron derived soil water contents are given in Figure 1. A linear relation exists and can be described by the equation

$$\Theta_g = 0.8313 + 1.45\ \Theta_v,\ r^{-2} = 0.83$$

where Θ_g is the gravimetric water content and Θ_v is the neutron volumetric water content. The factor 1.45 in the preceding equation represents the bulk density of the soil in the sampling depth. Thus, if the gravimetric soil water contents were multiplied by 1.45, it should result in volumetric water contents which should then match those calculated from the neutron equipment readings.

The use of the cadmium shielding around the probe significantly decreased the effects of any neutron moderating material around it. For example, counts obtained in a row of mature guayule plants were 4207+45.4 without the shield vs. 4056+60.8 with the shield, and similarly 10718+34 vs 10178+104 for the standard reference absorber.

SUMMARY

A properly field calibrated neutron probe gave comparable soil water contents as those derived from soil sampling. The equipment is labor saving and provides nondestructive sampling, which is particularly important in direct seeding experiments where minimal bed disturbance is required. The use of cadmium shielding around the probe helped to cut down on extraneous readings and increased the reliability of the measurements.

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PERSONNEL

F. S. Nakayama, D. A. Bucks, D. Powers (Cooperator), J. Martinez

TITLE: GERMPLASM DEVELOPMENT AND DOMESTICATION OF CUPHEA AND OTHER NEW CROP SPECIES

SPC: 2.1.03.1.a CRIS Work Unit: 5344-21000-001

INTRODUCTION

Extensive irrigation is essential to produce high yields of traditional crops in the arid Southwest. If agriculture is to persist in the region, new crops with lower water usage will be needed. Numerous studies have clearly demonstrated the need and potential of research to create and develop new or alternative crops.

Raw materials for the U. S. oleochemical industry are frequently imported and significantly add to this country's unfavorable balance of payment problem. The primary source of lauric acid for manufacturing soaps, detergents, lubricants and other related products is imported coconut and palm kernel oils. Likewise, the U. S. is heavily dependent upon imported castor oil for its total supply of hydroxy fatty acids, a strategic material used in the production of lubricants, plasticizers, protective coatings, surfactants, and pharmaceuticals. Seed oils from species of *Cuphea* and *Lesquerella* are viable candidates for domestic production of lauric acid and other medium-chain fatty acids, and for hydroxy fatty acids, respectively (2,3,6,9).

PROCEDURE

Previous research at this location has demonstrated that most species of cuphea are not adapted to the high temperature conditions during the growing season throughout the arid Southwest. This constraint is largely due to a failure to set adequate amounts of seed. However, research at this location provides valuable service to the national cuphea research effort by developing improved germplasm and segregating breeding material. This material is provided to cooperating state and federal scientists for evaluation in Oregon, Iowa, Georgia, and other locations. Our germplasm enhancement research efforts primarily concentrates on both intra- and interspecific hybridization (1,2,4,5). The primary objective is to obtain new genetic combinations that may be useful in the development of new cultivars for production in more temperate growing area. A new compact growth habit found in *C. leptopoda* has been characterized, and may be of value in the new germplasm being developed (7). In contrast to cuphea, lesquerella is native to arid and semiarid areas and has high potential for domestication and production in the arid Southwest (3,6,9). Research methods employed with lesquerella for development of improved germplasm concentrates on utilizing conventional plant breeding, selection, and genetic methods. Cooperative research on determining water requirements and other crop management factors is conducted with other scientists in the Arid Zone Crop Production Research Unit of the U.S. Water Conservation Laboratory.

RESULTS AND DISCUSSION

Cuphea:

To date, a total of 17 species in three different sections of the genus have been used as parents in the production of new interspecific hybrids (Table 1). Of the total, eight species have been involved in 18 morphologically and cytologically confirmed successful interspecific hybrids (Table 2). In all instances successful hybrids have as yet only involved species within the generic section Heterodon. All of the hybrids, except for those between *C. procumbens* and *C. llavea*, are sterile due to meiotic irregularities (1).

The seven hybrids involving reciprocal crosses of different accession of *C. llavea* and *C. procumbens* have exhibited a relatively high degree of fertility. Both species have the same chromosome number (N=9), and chromosome pairing in the hybrids is essentially normal at meiosis and the hybrids are all self-fertile (1). This is somewhat surprising since the two parental species are morphologically distinct. *Cuphea procumbens* is a herbaceous annual with large, 6-petalled flowers, while *C. llavea* is an erect growing, semi-woody perennial with flowers exhibiting long calyx tubes and only two dorsal petals. In general the hybrids are intermediate in plant and flower characteristics, and usually exhibit some degree of perenniality. F_2 populations of several of the hybrids were grown at Ames, IA, Corvallis, OR, and Tifton, GA, during the 1986 growing season. F_3 populations were grown at Ames, IA in 1987. Some F_2 and F_3 plants exhibited a more determinate flowering habit, more compact grouping of flowers in the inflorescence, and reduced seed loss by shattering. However, none of the material appears to have removed the major constraints to high levels of seed production. Some of these hybrids do exhibit interesting horticultural features (1,4,5,7). Hybrid 1016 produces attractive bright red flowers on semi-woody, erect stems. The hybrid is perennial and can be readily propagated by stem cuttings. For two years, a plant of 1016 has flowered profusely in the field in Phoenix, AZ during the summer months where maximum daytime temperatures regularly exceed 38° C. A cooperative effort has been initiated with Dr. Mark Roh, Research Horticulturist at the Florist and Nursery Laboratory at the Beltsville Agricultural Research Center to evaluate the hybrids' potential as a new pot or bedding plant (5).

One of the most interesting hybrids is 1006 (*C. leptopoda* x *C. laminuligera*), which is the first successful hybrid between *Cuphea* species in different fatty acid groups (1). The hybrid is very vigorous and flowers profusely, but is highly sterile due to irregular chromosome pairing at meiosis even though both parents have the same chromosome number (N=10). We were successful in restoring fertility in five hybrid plants by doubling the chromosome number following treatment with colchicine. Surprisingly, the fertile amphidiploids were self fertile and produced abundant, viable seed by natural self pollination in the greenhouse. Both parents are naturally cross pollinated and normally require an insect vector to effect pollination. Seed set by natural self pollination would be a desirable feature for a commercial cultivar since seed production in the field would not require bees or other pollinating insects.

Adequate quantities of seeds were collected on four of the five fertile 1006 (C. leptopoda x C. laminuligera) amphidiploid plants that would allow chemical analysis of the fatty acid distribution. In addition, one progeny plant from one of the amphidiploids also produced an adequate quantity of seeds for analysis. These seeds plus those of the parental species were sent to Dr. Robert Kleiman at the NRRC in Peoria, IL for analysis. Additionally for comparison, seeds of various accessions of C. llavea and C. procumbens and their fertile reciprocal hybrids were also sent to Peoria for analysis (Table 3).

As expected, the reciprocal hybrids of the C10:0 x C10:0 crosses involving C. llavea x C. procumbens exhibited the C10:0 fatty acid pattern typical of the two parental species (8). The fatty acid profile of the C. leptopoda x C. laminuligera amphidiploid hybrid was essentially identical to C. leptopoda, the C10:0 parent. It may be inferred that carbon chain elongation in the biosynthesis of the seed oil fatty acids is controlled by a dominant gene. Attempts are being made to backcross the amphidiploid to the original parental species, which may provide valuable information on the inheritance and biosynthesis of seed oil fatty acids (Table 4). In addition, special effort is being made to effect the backcross of the amphidiploid to C. laminuligera and outcross to C. lutea, another C12:0 rich species, to obtain useful genetic recombination and segregation. If we are successful, we may be able to produce very useful lauric acid (C12:0) rich germplasm that can be utilized in cultivar development. Superficial inspection of the data in Table 4 appears to indicate that the backcross to C. laminuligera and perhaps the outcross to C. lutea are more difficult to achieve than the backcross to C. leptopoda. However, results of these new crosses are as yet unknown until the progenies are grown out and evaluated. Additional concentrated efforts are currently being made to successfully complete these very important crosses.

Seeds of four of the original amphidiploid hybrids plus that produced on 26 progeny plants from three of the original plants have been distributed to Dr. W. W. Roath, Ames, IA, and Dr. S. J. Knapp, Corvallis, OR, for field evaluation during the 1988 growing season (Table 5).

A series of new Cuphea interspecific hybrids have been attempted. Twenty new putative hybrids involving 11 species in three sections of the genus were made by Dr. D. T. Ray and associates under a broadform cooperative agreement at the University of Arizona in 1985-86 (Table 6). In addition, 16 new putative hybrids involving the three related species, C. procumbens, C. llavea, and C. caesariata were also made at the University of Arizona (Table 7). Limited greenhouse facilities have delayed growing out these crosses to determine if interspecific hybrids have been effected.

A new series of six crosses have been made in Phoenix in an attempt to hybridize species currently undergoing domestication, and that also vary in fatty acid seed oil content (Table 8). This effort is a continuing activity.

Lesquerella:

The 1986-87 planting of lesquerella was less than successful. In contrast to previous years the planting was made on a level soil surface rather than on raised beds. The plantings were made on 17 October 1986 and flood irrigated. This resulted in excessive crusting and poor emergence. The water use study was replanted on 2 December 1986. Good plant stands were obtained but biomass and seed yields were reduced by at least 50 percent. The lesquerella breeding plots and the replicated yield trial of the 10 best half-sib families were not replanted. A total of 45 single plant selections were made from the breeding plots. Sixteen of the selections were specifically made for increased plant height from a bulk population of tall plant selections made in 1986.

On October 1 and 2, 1987, single row half-sib progeny observation plots varying from 3 to 100 meters in length (depending on availability of seed) were planted of each of the single plant selections made in the 1986-87 planting. In addition, 285 single row plots ranging from 3 to 50 meters in length were planted of seed of single plant selections made by Dr. D. D. Rubis, University of Arizona, in 1977. These plots will be observed for plant growth and yield, and will provide a sizeable population for further selection.

In addition, two replicated plantings were made. One is a repetition of last year's water use study and the other is designed to obtain more information on plant population and planting methods. Both broadcast seed application and row planting with a Stanhay seeder are included. On 3 December 1987, plant populations were established by thinning rowed plots to achieve populations of 400,000, 600,000, and 800,000/ha plus unthinned rows estimated to be in excess of 1 million plants/ha. In the broadcast treatments, plants were thinned to achieve a population of 1 million plants/ha. It is anticipated that these plots will be harvested in June 1988.

SUMMARY AND CONCLUSIONS

Good progress is being made on effecting successful hybridization among species of *Cuphea*. The fertile amphidiploid hybrid of *C. leptopoda* x *C. laminuligera* holds promise for development as a new crop since it is very vigorous, and set abundant large sized seeds by self pollination. Unfortunately, the predominant fatty acid in the seed oil is capric (C10:0) rather than lauric acid (C12:0), which may limit its current usefulness. Extensive effort is being made to backcross the hybrid to its C12:0 parent, *C. laminuligera*, to encourage segregation and ultimate selection of high lauric acid production in an agronomically adapted and productive plant.

Lack of adequate greenhouse space has severely hampered efforts to grow out progeny from crosses. Steps have been taken for the purchase and erection of a new greenhouse in 1988, which will greatly facilitate these efforts.

New data gathered on lesquerella were limited due to problems of stand establishment. This problem was resolved during the 1987-88 planting by using sprinkler applications of irrigation water to promote uniform seed germination and emergence. It is anticipated that good yields will be obtained in the yield experiments currently in progress.

Yields from previous cultural experiments (± 1,200 kg/ha), and from progeny of selections (± 1,550 kg/ha) are very encouraging, and provide a strong rationale for continued breeding and agronomic research. With adequate research, it is concluded that development of lesquerella as a new crop for the production of hydroxy fatty acids under arid environments could be accomplished within six to eight years.

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Table 1. Cuphea species used as parents in confirmed and putative interspecific hybrids. 1983-87.

Species	Chromosome Number (n)	Predominant Fatty Acid	Accessions Used
Section Heterodon:			
C. angustifolia	12	C10:0	A0005, A0145
C. caesariata	18	C10:0	A0073, A0379
C. crassiflora	12	C10:0	A0097
C. laminuligera	10	C12:0	A0142, A0265, A0371, A0384
C. lanceolata	6	C10:0	A0224, A0226, A0236, A0252
C. leptopoda	8	C10:0	A0264
C. leptopoda	10	C10:0	A0065, A0072, A0383, A0385
C. llavea	9	C10:0	A0061, A0064, A0069, A0074
C. lophostoma	8	C10:0	A0127
C. lutea	14	C12:0	A0144, A0381
C. procumbens	9	C10:0	A0002, A0100, A0235, A0242, A0263
C. wrightii	22	C12:0	A0261
C. wrightii x C. tolucana	22	C12:0	A0260
C. viscosissima	6	C10:0	A0049
C. leptopoda x C. laminuligera	20	C10:0	1006 (A0065 x A0142)
Section Diploptychia:			
C. cynea	6,30	C8:0	A0150
C. hookeriana	±40?	C8:0	A0024
Section Melvilla:			
C. caeciliae	30	C10:0	A0206
C. ignea	15	C10:0	A0057

Table 2. Summary of cytologically confirmed successful interspecific hybrids among eight *Cuphea* species.

Cross Number	Female Parent		Male Parent		Cross Produced by (T or P)[a]	Chromosome Number (2N)	Reproductive Fertility (F or S)[b]
1003	A0242	C. procumbens	A0072	C. leptopoda	P	19	S
1006	A0065	C. leptopoda	A0142	C. laminuligera	P	20	S
1006[c]	A0065	C. leptopoda	A0142	C. laminuligera	P	40	F
1019	A0235	C. procumbens	A0264	C. leptopoda	P	17	S
1010	A0061	C. llavea	A0100	C. procumbens	P	18	F
1014	A0069	C. llavea	A0263-2	C. procumbens	P	18	F
1016	A0235	C. procumbens	A0074(?)	C. llavea	P	18	F
1026	A0002	C. procumbens	A0074	C. llavea	T	18	F
1027	A0263-1	C. procumbens	A0074	C. llavea	T	18	F
1029	A0263-5	C. procumbens	A0074	C. llavea	T	18	F
87-6	A0263	C. procumbens	A0069	C. llavea	T	18	F
87-4	A0263	C. procumbens	A0379	C. caesariata	T	27	S
1020	A0263-6	C. procumbens	A0097	C. crassiflora	T	21	S
1032	A0235	C. procumbens	A0236(?)	C. lanceolata	P	15	S
87-3	A0263	C. procumbens	A0226	C. lanceolata	T	15	S
1024	A0224	C. lanceolata	A0074	C. llavea	T	15	S
87-5	A0226	C. lanceolata	A0074	C. llavea	T	15	S
87-7	A0226	C. lanceolata	A0379	C. caesariata	T	24	S
1025	A0252	C. lanceolata	A0127	C. lophostoma	T	14	S

[a] T = University of Arizona, Tucson, P = U.S. Water Conservation Lab., Phoenix.
[b] F = fertile with viable seeds, S = sterile with no seeds set.
[c] 1006 fertile amphidiploid produced by colchicine treatment.

Table 3. Fatty acid distribution in seed oils of four cuphea species and two interspecific hybrids.

Parents and Hybrids	Predominant Fatty Acid	Number of Samples		1000 Seed Weight (g)	Fatty Acid Distribution (%) C8:0	C10:0	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	C20:0	Other
C. laminuligera	C12:0	1	Mean ($\bar{x}$)	2.18	0.4	19.6	59.7	7.2	3.0	0.3	2.5	6.8	0.3	0.1	0.1
C. leptopoda	C10:0	1	Mean ($\bar{x}$)	4.20	1.2	87.0	1.4	0.4	2.2	0.5	2.8	4.2	0.1	0.1	0.1
C. leptopoda x C. laminuligera	C10:0	5	Mean ($\bar{x}$)	5.24	1.4	87.6	1.4	1.1	2.4	0.4	3.0	2.3	0.2	0.1	0.1
			SE	0.236	0.02	0.21	0.05	0.02	0.05	0.02	0.10	0.14	0.05	0.0	0.05
			CV	10.1	3.8	0.5	8.7	5.2	4.6	10.6	7.2	13.5	49.8	0.0	91.3
C. llavea	C10:0	4	Mean ($\bar{x}$)	3.07	1.1	84.8	1.7	0.9	2.3	0.4	3.7	4.4	0.2	0.1	0.2
			SE	0.074	0.07	0.48	0.06	0.06	0.12	0.03	0.10	0.28	0.03	0.0	0.05
			CV	4.8	12.9	1.1	7.3	14.4	10.8	12.8	5.5	12.6	23.1	0.0	42.6
C. procumbens	C10:0	8	Mean ($\bar{x}$)	3.59	0.9	80.6	1.8	1.3	3.1	0.8	6.1	4.7	0.3	0.1	0.3
			SE	0.131	0.05	0.87	0.07	0.21	0.25	0.06	0.35	0.24	0.03	0.01	0.03
			CV	10.3	13.9	3.1	11.3	45.2	22.5	21.2	16.0	14.3	29.0	31.4	32.2
C. llavea x C. procumbens	C10:0	3	Mean ($\bar{x}$)	4.65	1.0	84.5	1.7	1.2	2.5	0.5	4.3	3.7	0.2	0.1	0.2
			SE	0.244	0.19	0.88	0.09	0.22	0.26	0.03	0.58	0.12	0.03	0.0	0.03
			CV	9.1	31.1	1.8	9.2	30.7	18.3	12.4	23.7	5.6	24.7	0.0	24.7
C. procumbens x C. llavea	C10:0	8	Mean ($\bar{x}$)	4.12	1.0	84.6	1.5	0.8	2.2	0.6	4.5	4.1	0.3	0.1	0.2
			SE	0.182	0.05	0.53	0.03	0.04	0.08	0.04	0.40	0.14	0.02	0.0	0.03
			CV	12.5	13.5	1.8	4.8	15.0	10.6	21.1	24.8	9.4	22.3	0.0	46.3

Table 4. Summary of attempted backcrosses and outcrosses of the fertile amphidiploid, 1006 (*C. leptopoda* x *C. laminuligera*), the first successful interspecific hybrid between different fatty acid groups.

New Cross Numbers	Female Parent	Male Parent	Crosses Attempted (No.)	Successful Crosses (No.)	Seeds Produced (No.)	Seeds/ Successful Cross (No.)
Backcross to *C. laminuligera* (C12:0):						
1057	1006	A0371	253	18	45(14?)[a]	2.5
----	1006[b]	A0371	294	0	0	0
1058	A0371	1006	345	23	60(60?)	2.6
1056	1006[c]	A0384	320	30	82	2.7
1056	1006	A0384	5	0	0	0
----	A0384	1006	18	0	0	0
Backcross to *C. leptopoda* (C10:0):						
1059	1006	A0383	91	10	52(10?)	5.2
1060	A0383	1006	80	1	1(1?)	1.0
1061	1006	A0385	166	44	167	3.8
1062	A0385	1006	164	4	6(2?)	1.5
Outcross to *C. lutea* (C12:0):						
----	1006	A0144	53	0	0	0
1063	A0144	1006	11	3	7(5?)	2.3

[a] Number of seeds with questionable viability.
[b] Sterile original interspecific hybrid.
[c] Cross effected without emasculation of female parent.

Table 5. Distribution of 1006 (*Cuphea leptopoda* x *C. laminuligera*) Fertile Amphidiploid Seed for Field Evaluation

Line	W. W. Roath Ames, IA (g)	S. J. Knapp Corvallis, OR (g)		Phoenix Remnant (g)
1006-1	1.0	7.0		0.1
1006-1-1	0.5	4.5		2.0
1006-1-2	0.2	—		0.1
1006-1-3	0.2	—		0.2
1006-1-4	0.2	—		0.1
1006-1-5	0.2	0.2		0.2
1006-1-6	0.2	0.8		0.2
1006-1-7	0.2	1.0		0.2
1006-1-8	0.2	2.8		0
1006-1-9	0.2	1.2		0.3
1006-1-10	0.2	1.4		0.3
1006-1-11	0.2	0.6	Bulk	0.1
1006-1-12	0.2	0.7	12.5 g	0
1006-1-13	0.2	0.5		0
1006-1-14	0.2	0.6		0.1
1006-1-15	0.2	0.4		0
1006-1-16	0.2	0.4		0
1006-1-17	0.2	0.7		0
1006-1-18	0.2	1.1		0.1
1006-1-19	0.2	0.1		0
1006-2	0.4	1.0		0.2
1006-4	—	0.1		0.1
1006-4-1	0.5	2.2		0
1006-4-2	0.5	5.3	Bulk	0
1006-4-3	0.5	0.8	12.9 g	0.2
1006-4-7	0.5	0.3		0.2
1006-4-8	0.5	2.3		0.2
1006-4-11	0.5	2.0		0.2
1006-5	0.2	0.7		0.1
1006-5-1	0.3	—		0

Table 6. Summary of 20 new putative Cuphea interspecific hybrids made at the University of Arizona, 1985-1986, involving 11 species in 3 sections of the genus.

New Cross Numbers	Female Parent		Male Parent		Successful Crosses (No.)	Seeds Produced (No.)	Seeds/ Successful Cross (No.)
1070	A0057	C. ignea	A0005	C. angustifolia	2	11(3?)[a]	5.5
1071	A0057	C. ignea	A0145	C. angustifolia	1	4(4?)	4.0
1072	A0064	C. llavea	A0145	C. angustifolia	1	2	2.0
1073	A0145	C. angustifolia	A0127	C. lophostoma	1	2	2.0
1074	A0005	C. angustifolia	A0100	C. procumbens	1	3	3.0
1075	A1027	C. lophostoma	A0145	C. angustifolia	2	8(1?)	4.0
1076	A0127	C. lophostoma	A0150	C. cynea	1	2	2.0
1077	A0127	C. lophostoma	A0226	C. lanceolata	1	1	1.0
1078	A0127	C. lophostoma	A0146-6	C. laminuligera	1	2	2.0
1079	A0024	C. hookeriana	A0145	C. angustifolia	1	6(3?)	6.0
1080	A0024	C. hookeriana	A0206	C. caecilia	1	2	2.0
1081	A0024	C. hookeriana	A0150	C. cynea	5	33	6.6
1082	A0024	C. hookeriana	A0069-3	C. llavea	6	38	6.3
1083	A0074-F	C. llavea	A0226	C. lanceolata	2	2	1.0
1084	A0074-F	C. llavea	A0065	C. leptopoda	1	1	1.0
1085	A0261-7-9-1	C. wrightii	A0069-3	C. llavea	2	12	6.0
1086	A0265	C. laminuligera	A0074-F	C. llavea	2	9	4.5
1087	A0263	C. procumbens	A0065	C. leptopoda	1	1	1.0
1088	A0206	C. caeciliae	A0057	C. ignaa	9	32	3.6
1089	A0057	C. ignea	A0206	C. caeciliae	20	170	8.5

[a] Number of seeds with questionable viability.

Table 7. Summary of 16 new putative Cuphea interspecific hybrids among C. procumbens, C. llavea, and C. caesariata made at the University of Arizona, 1985-1986.

New Cross Numbers	Female Parent		Male Parent		Successful Crosses (No.)	Seeds Produced (No.)	Seeds/ Successful Cross (No.)
1090	A0100	C. procumbens	A0061	C. llavea	3	16	5.3
1091	A0069-3	C. llavea	A0100-3	C. procumbens	4	12	3.0
1092	A0069-3	C. llavea	A0100-2	C. procumbens	?	10	?
1093	A0074-F-2	C. llavea	A0100-2	C. procumbens	9	37	4.1
1094	A0074-F-1	C. llavea	A0100-1	C. procumbens	6	30	5.0
1095	A0263	C. procumbens	A0061	C. llavea	?	8	?
1096	A0263	C. procumbens	A0069	C. llavea	?	10	?
1097	A0263	C. procumbens	A0069-3	C. llavea	1	2	2.0
1098	A0263	C. procumbens	A0074-F-1	C. llavea	?	53	?
1099	A0073	C. caesariata	A0064	C. llavea	1	2	2.0
1100	A0073	C. caesariata	A0100-3	C. procumbens	1	1	1.0
1101	A0263	C. procumbens	A0073	C. caesariata	10	54	5.4
1102	A0064	C. llavea	A0379	C. caesariata	3	15	3.0
1103	A0379	C. caesariata	A0074-F-1	C. llavea	2	3	1.5
1104	A0379	C. caesariata	A0235	C. procumbens	1	1	1.0
1105	A0379	C. caesariata	A0263	C. procumbens	1	2	2.0

Table 8. Summary of new interspecific hybrids attempted involving species with differing predominant seed oil fatty acids.

New Cross Numbers	Female Parent	Male Parent	Crosses Attempted (No.)	Successful Crosses (No.)	Seeds Produced (No.)	Seeds/ Successful Crosses (No.)
1064	A0371 C. laminuligera (C12:0)	A0381 C. lutea (C12:0)	89	6	14(14?)[a]	2.3
1065	A0144 C. lutea (C12:0)	A0371 C. laminuligera (C10:0)	58	9	13(13?)	1.4
1066	A0226 C. lanceolata (C10:0)	A0144 C. lutea (C12:0)	34	1	2	2.0
---	A0144 C. lutea (C12:0)	A0226 C. lanceolata (C10:0)	54	0	0	0
1067	A0226 C. lanceolata (C10:0)	A0049 C. viscosissima (C10:0)	165	47	221	4.7
1068	A0252 C. lanceolata (C10:0)	A0049 C. viscosissima (C10:0)	58	11	50	4.5
---	A0381 C. lutea (C12:0)	A0049 C. viscosissima (C10:0)	34	0	0	0
1069	A0049 C. viscosissima (C10:0)	A0381 C. lutea (C12:0)	33	2	3(3?)	1.5
---	A0049 C. viscosissima (C10:0)	A0144 C. lutea (C12:0)	2	0	0	0

[a] Number of seeds with questionable viability.

TITLE: GUAYULE GERMPLASM ENHANCEMENT FOR INCREASING NATURAL RUBBER AND RESIN PRODUCTION

SPC: 2.1.03.1.b CRIS WORK UNIT: 5344-21000-002

INTRODUCTION

Guayule (*Parthenium argentatum* Gray) has the potential of becoming an important domestic source of natural rubber. Although some progress has been achieved in increasing yields, for guayule to become an economically feasible crop of the southwest desert, further increases in rubber yield, either by increasing biomass or the plant's rubber content, are necessary.

Providing the variability for these desired traits is present in available germplasm, the plant breeder must find a means of selecting for these two traits. It is obvious that biomass can be visually estimated, and it is therefore easier to select for this trait in comparison to the plant's rubber content. Due to practical considerations such as harvesting and processing, high rubber content becomes more desirable than extremely large plants. It is hoped that measured characters can be found to predict both traits in order to aid the plant breeder. The objective of this study was to find useful relationships between rubber content and yield, with plant morphological and biomass characteristics that might be used as a selection criteria for improving guayule rubber yields. The amount of variability, both among and between guayule lines, was also examined to determine the amount of success in selection for these qualities.

Field Procedures:

A diverse guayule breeding population was established at the Wong Farm, located near Marana, AZ, in 1982. These selections were all believed to reproduce by facultative apomixis. Plants were transplanted into single row plots with 0.36 m between plants and 1 m row spacing. Each plot was a progeny row and consisted of approximately 30 plants. The field was furrow irrigated.

Out of a total population of 234 uniform progeny rows, 42 lines were selected for study, on the basis of high rubber concentration, yield, and regrowth from the previous year's harvest. In February 1987, ten plants from these 42 plots were harvested and analyzed.

The variables measured in this study were percent rubber, rubber yield (g/plt.), plant height (cm), width (cm) and volume (m^3), fresh and dry weight (kg/plt.), mean stem diameter (cm), total and mean stem area (cm^2), total and mean stem circumference (cm), total circumference/total area (TC/TA) (cm^{-1}), stem number, and percent dry weight.

Plants were harvested by clipping the entire top growth 10 cm above ground level and analyzed for rubber content by near infrared (NIR) analysis. The stem cross sectional area, stem circumference, and the quotient of the two, were calculated from stem diameter and stem number measurements.

Statistics performed on these data include: correlation coefficients (Table 1), linear regressions with percent rubber and rubber yield as dependent variables (Tables 2 and 3), means, standard errors and coefficients of variation (cv) Table 4, and standard deviations (SD), Table 5.

The method of linear regression used was a subset selection method. If there are 13 independent variables, all possible combinations of one independent variable are calculated, and then for two independent variables, and so forth until all 13 variables are included in a subset. For each of these combinations the one with the highest R^2 was chosen. This yielded a subset with the highest R^2 value for each of the 13 combinations of independent variables. A criterion to account for the bias of the model is called Mallows' Cp criterion. The model rating in Tables 2 and 3 are based on this value.

RESULTS AND DISCUSSION

Correlations were performed to determine the extent of relationships among the variables of the 42 lines. It appears that none of the variables are highly correlated with percent rubber even though the negative correlation coefficients of plant widths, volume, dry and fresh weights were all highly significant (Table 1). The implied relationship is that as biomass increases, percent rubber decreases. Although the negative r values for the four variables are significant, only slightly more than 25% of the variation is accounted for in each of these correlations.

Rubber yield on the other hand had higher significant correlations with almost every variable (Table 1). The highest correlation for rubber yield was with fresh and dry plant weight ($r = 0.84$ and 0.85, respectively). These data agree very closely with previous studies.

It is apparent that fresh and dry weight are the best predictors for rubber yield. As biomass increases, rubber yields increase. For practical purposes however, a predictor of biomass is desirable since it is a destructive measurement. Plant volume, mean stem diameter, total stem circumference and TC/TA all correlate fairly well with both rubber yield an dry weight. Total stem circumference seemed to be more highly correlated to rubber yield than plant volume. However, the difference is not large and the average r^2 values are 0.56 for the former and 0.50 for the latter. When total stem circumference and plant volume are correlated to dry weight, the average r^2 values are 0.52 and 0.67 respectively, meaning that one-half to two-thirds of the variability is herein accounted for. For practical purposes plant volume is more easily obtained in the field and would serve as the best predictor.

Two regression models were used to determine the relationships between percent rubber and total rubber with the other variables. In the first model, shown in Table 2, percent rubber was the dependent variable.

The R^2 ranged between 0.38 for plant dry weight along to 0.59 when all 13 variables were included. When plant volume, fresh weight, dry weight and percent dry weight are included in the subset, ($R^2 = 0.51$), the subset is rated as the best predictor of rubber content according to Mallows' Cp criterion.

The data for total rubber in Table 3, has a wider range of R^2 values. However, when four variables are added to the subset, this range narrows considerable. This subset has an R^2 value of 0.85 and the best rating of all combinations. The four variables were height, width, volume, and dry weight which are all biomass related. When all 13 variables are included in the subset, the R^2 value is increased only slightly to 0.88, and is rated eleventh.

The second regression with total rubber as the dependent variable, attributes up to 88% of the variability. From the two models it can be seen that percent rubber is not easily predicted. However, when a few biomass variables are utilized, total rubber can be predicted more accurately.

Means, standard errors and coefficients of variation (CV) for the different variables are presented in Table 4. Theoretically, each plot represents a different genotype, however, the high range of variability observed by the CV's were similar to those expected in a sexually reproducing population. If these differences are heritable, this is desirable in a breeding program since it offers an opportunity for improvement through selection. The only variable with a low CV was percent dry weight. In guayule it appears that the plants' water content remains constant, on a percentage bases, even though there are obvious differences in the growth habits among the lines. These differences in growth were reflected in the high CV for both dry and fresh weight.

Other measurements of biomass include plant height, width and volume. The variability in height and width were of nearly the same magnitude, and similar to the variability for percent rubber (Table 4). On the other hand, volume had nearly triple the variability due to the non-linearity of the measurements, taking into account the square of the radius in the calculation. The amount of variability was also large for fresh and dry weight, although these are direct measurements. The variability in dry weight and percent rubber are of potential interest to the plant breeder since these two factors determine total rubber yield.

A comparison was made of the standard deviations (SD) among the total population from 1987 with the standard deviation within each of the 42 selected lines in 1987 to assess variability (Table 5). Each of the 42 lines consisted of 10 plants, totalling 420 plants, which were used to calculate the SD for the whole population. The lines exceeding the mean and SD value, indicating high variability within the line, are underlined. Thus, 42 different genotypes were tested. It is apparent from Table 5 that a large amount of variability exist within some of these guayule lines.

This variability is hopefully genetic and can be used in selection. The parental plants were apomictic and polyploid. Even though they are apomictic this process is not a uniform in all genotypes. Varied degrees and combinations of apomeiosis may occur. It is possible for reduction and unequal chromosomal segregation to take place contributing to a varied degree of aneuploidy. The result of the chromosomal imbalance is a genetic imbalance causing phenotypic variation within a line. Mitotic recombination and somaclonal variation are also possible sources of variation.

SUMMARY

These data indicate that rubber yield may be predicted with a high degree of confidence. Since these measured variables are growth related they are able to accurately predict biomass which is used to calculate rubber yield. Rubber percentage on the other hand is not as highly correlated to the variables measured herein and in any other published study. The limitation of these models and amount of difficulty and time consumed in making these kinds of measurements may lead the guayule breeder to the conclusion that more accurate and simpler plant sampling techniques for rubber percentage need to be developed.

This study has also shown that a large amount of variability exists among and between the guayule lines tested. If the variability is genetic indicating progress should be possible through selection. The implication from these data is that genetic segregation does occur to varying degrees in apomictic guayule lines. For obvious reasons, the amounts of variation are important for the plant breeder, the grower, and the seed producer to recognize. The challenge for the breeder is to utilize the lines having large amounts of variation and then have the ability to control the variability once desirable traits have been selected and established within lines.

PERSONNEL

D. A. Dierig and A. E. Thompson
D. T. Ray, University of Arizona, cooperating

Table 1. Correlation coefficients of variables of the data set from 42 guayule lines harvested in 1987.

Variables	Rubber content (%)	Rubber yield (kg/plant)	Dry weight (kg/plant)
Rubber content (%)	--	-0.17	-0.62***
Rubber yield (kg/plant)	-0.17	--	0.85***
Height (cm)	-0.33*	0.62***	0.65***
Width (cm)	-0.53***	0.59***	0.74***
Volume (m^3)	-0.58***	0.65***	0.83***
Fresh weight (kg/plant)	-0.62***	0.84***	0.99***
Dry weight (kg/plant)	-0.62***	0.85***	--
% Dry weight	0.07	0.22*	0.14
Stem number	0.34*	-0.41**	-0.51***
Mean stem diameter (cm)	-0.42**	0.68***	0.71***
Total stem circumference (cm)	-0.33*	0.76***	0.76***
Total stem area (cm^2)	0.05	0.35*	0.14
Mean stem area (cm^2)	-0.42**	0.68***	0.72***
Mean stem circumference (cm)	-0.47**	0.66***	0.73***
Total circum/total area (cm^{-1})	0.41**	-0.67***	-0.73***

*, **, *** = Significantly different from 0 at the 0.05, 0.01 and 0.001 probability levels.

Table 2. Thirteen subsets of a regression model with percent rubber as the dependent variable for 42 lines harvested in 1987. Numbers 1 through 13 each include a different subset. The first column is the multiple coefficient of determination (R^2). The model rating column is based on a statistical criteria for selecting the model. The third column is the intercept. The remaining columns are slope values for the respective variables.

No.	R^2	Model rating	Inter-cept	Plant height (cm)	Plant width (cm)	Plant volume (cm^3)	Fresh weight (kg/plant)	Dry weight (%)	Dry weight (kg/plant)	Stem diameter (cm)	Stem circum. (cm)	Mean stem circum. (cm)	Stem area (cm^2)	Mean stem area (cm^2)	Total circum./ total area (cm^{-1})	Stem number
1.	0.38	5	9.54						-1.77							
2.	0.41	6	6.10					0.05	-1.84							
3.	0.47	2	-4.11	0.08	0.15	-7.09										
4.	0.51	1	-6.39			-1.31	10.56	0.22	-14.81							
5.	0.52	3	-6.10	0.02		-1.66	9.87	0.20	-13.90							
6.	0.54	4	-11.28	0.05	0.09	-4.91	8.60	0.17	-11.78							
7.	0.55	7	-16.75	0.05		-2.48	13.11	0.24	-17.90					1.02	1.41	
8.	0.56	8	-19.56	0.06	0.07	-4.99	11.79	0.22	-15.90					0.90	1.19	
9.	0.58	9	-25.10	0.08	0.16	-8.37	13.39	0.23	-17.42	3.19	-0.10					0.24
10.	0.58	10	-29.65	0.09	0.19	-9.47	15.13	0.26	-19.67	24.93	-0.12	-6.65				0.28
11.	0.59	11	-25.45	0.07	0.16	-7.77	12.24	0.21	-16.05	10.17	-0.27		0.28	-3.38		0.46
12.	0.59	12	-27.89	0.07	0.15	-7.64	12.96	0.23	-16.97	9.12	-0.27		0.34	-3.00	0.90	
13.	0.59	13	-29.13	0.08	0.16	-8.07	13.58	0.24	-17.77	15.15	-0.26	-2.03	0.32	-2.74	0.85	0.38

Table 3. Thirteen subsets of a regression model with total rubber as the dependent variable for 42 lines harvested in 1987. Numbers 1 through 13 each include a different subset. The first column is the multiple coefficient of determination (R^2). The model rating column is based on a statistical criteria for selecting the model. The third column is the intercept. The remaining columns are slope values for the respective variables.

No.	R^2	Model rating	Inter-cept	Plant height (cm)	Plant width (cm)	Plant volume (cm^3)	Fresh weight (kg/plant)	Dry weight (%)	Dry weight (kg/plant)	Stem diameter (cm)	Stem circum. (cm)	Mean stem circum. (cm)	Stem area (cm^2)	Mean stem area (cm^2)	Total circum./total area (cm^{-1})	Stem number
1.	0.73	13	31.9						45.32							
2.	0.78	12	-0.2						43.54		0.69					
3.	0.80	9	7.1						37.24		1.01					-1.05
4.	0.85	1	-230.2	1.39	2.97	-129.6			69.88							
5.	0.86	2	-284.9	1.26	2.79	-124.9	53.75	1.00								
6.	0.86	3	-282.6	1.25	2.81	-124.0	51.45	0.92				1.31				
7.	0.87	4	-327.1	1.38	2.51	-118.9	53.78	0.95				6.32			11.15	
8.	0.87	6	-355.1	1.33	2.37	-114.5	80.91	1.39	-37.00			7.56			12.35	
9.	0.88	5	-261.5	0.93	2.00	-88.7			66.03		-3.62	63.67	5.37	-84.26		5.79
10.	0.88	7	-325.8	1.01	2.14	-97.7	50.65	0.82			-3.17	56.33	4.33	-69.32		5.44
11.	0.88	8	-333.8	1.02	2.11	-96.9	50.79	0.82			-3.22	55.56	4.65	-68.88	3.99	5.15
12.	0.88	10	-329.1	1.01	2.01	-93.7	50.72	0.82		-56.09	-3.19	72.85	4.69	-68.73	4.81	5.02
13.	0.88	11	-309.9	0.98	1.93	-90.1	38.55	0.63	16.09	-97.4	-3.25	87.38	4.88	-72.12	4.64	5.05

Table 4. Means, standard errors, and coefficients of variation of variables from 42 guayule lines harvested in 1987. Plots were harvested as a composite of ten plants.

Variable	Mean ± Standard error	Coefficient of variation
Rubber (%)	7.4 ± 0.18	15.8
Rubber (g/plant)	86 ± 3.3	25.3
Plant height (m)	0.91 ± 0.016	11.1
Plant width (m)	0.90 ± 0.018	13.1
Plant volume (m^3)	1.23 ± 0.06	34.1
Fresh weight (kg/plant)	1.65 ± 0.08	32.8
Dry weight (kg/plant)	1.19 ± 0.06	34.4
Mean stem diameter (mm)	11 ± 0.4	24.9
Mean stem area (mm^2)	15 ± 1.1	47.4
Mean stem circumference (mm)	36 ± 1.4	25.0
Total circumference/ total area (mm^{-1})	27 ± 0.8	20.2
Total stem area (mm^2)	191 ± 7.6	25.7
Total stem circumference (mm)	498 ± 11.3	14.7
Stem number	15 ± 0.6	27.5
Dry weight (%)	71 ± 0.6	5.5

Table 5. A comparison of the standard deviations (SD) of variables of 42 selected lines for 1987 compared to the SD of the entire population. The values in the row above line number 1 are the SD's of the entire population from 1987. Bold face underlined numbers indicate that the SD of that plot is greater than the SD for the entire population of 420 plants.

Line no.	Rubber (%)	Rubber (g/plt)	Height (m)	Width (m)	Volume (m^3)	Fresh weight (kg/plt)	Dry weight (kg/plt)	Stem diameter (mm)
	1.17	21.7	1.003	1.173	0.210	0.540	0.410	2.80
1.	**1.28**	**32.8**	0.985	**1.852**	**0.386**	**1.110**	**0.756**	**4.10**
2.	0.65	14.8	0.326	1.032	0.096	0.233	0.181	**3.04**
3.	0.86	21.5	0.432	0.979	0.119	0.426	0.321	1.20
4.	0.28	**25.0**	0.641	0.899	0.149	0.401	0.288	1.75
5.	0.35	21.6	0.349	0.792	0.132	0.401	0.290	**3.01**
6.	0.71	**22.1**	0.505	**1.228**	**0.234**	0.300	0.210	1.43
7.	0.72	**46.7**	0.775	**1.349**	0.189	**0.957**	**0.689**	**4.01**
8.	0.41	09.2	0.291	0.818	0.107	0.145	0.098	2.06
9.	0.63	16.6	0.803	1.135	0.152	0.293	0.219	1.81
10.	0.71	13.7	0.473	1.130	0.122	0.202	0.154	2.53
11.	0.82	10.6	0.694	0.384	0.056	0.139	0.127	1.12
12.	1.02	**41.0**	0.600	0.748	0.153	**0.605**	**0.479**	**4.05**
13.	0.87	**29.9**	0.612	1.065	0.170	0.486	0.350	**3.21**
14.	0.58	08.5	0.350	0.990	0.077	0.188	0.144	1.69
15.	0.92	**34.0**	**1.076**	**1.613**	**0.243**	**0.605**	**0.452**	**4.03**
16.	**1.42**	**52.5**	**1.003**	**1.179**	**0.262**	**0.899**	**0.604**	**4.49**
17.	0.62	**88.3**	**1.797**	**2.834**	**0.453**	**1.529**	**1.304**	**3.16**
18.	0.37	**64.9**	**1.705**	0.922	**0.297**	**2.149**	**1.463**	**3.86**
19.	0.59	**23.8**	0.846	0.998	0.119	0.418	0.273	1.61
20.	0.51	15.8	0.696	1.059	0.173	0.428	0.282	1.50

Table 5. Contd

Line no.	Rubber (%)	Rubber (g/plt)	Height (m)	Width (m)	Volume (m^3)	Fresh weight (kg/plt)	Dry weight (kg/plt)	Stem diameter (mm)
	1.17	21.7	1.003	1.173	0.210	0.540	0.410	2.80
21.	0.51	25.4	0.795	0.990	0.195	0.637	0.461	2.08
22.	0.73	37.4	1.474	1.159	0.349	1.029	0.759	3.16
23.	1.28	24.4	1.229	1.698	0.249	0.452	0.307	2.03
24.	1.56	14.2	1.303	1.257	0.225	0.398	0.276	1.52
25.	1.24	16.8	1.149	1.137	0.148	0.336	0.248	1.36
26.	1.00	17.6	0.732	1.000	0.129	0.338	0.257	1.56
27.	0.49	17.0	0.984	1.523	0.215	0.258	0.193	1.98
28.	0.84	35.1	0.931	1.559	0.242	0.527	0.379	1.19
29.	0.77	22.2	0.694	0.859	0.121	0.343	0.244	1.18
30.	0.35	17.5	1.100	1.302	0.202	0.324	0.250	1.20
31.	0.67	18.3	0.419	1.391	0.214	0.350	0.244	1.40
32.	0.68	28.4	0.401	0.794	0.115	0.484	0.337	1.87
33.	1.27	28.1	0.636	1.528	0.195	0.400	0.240	1.94
34.	0.81	32.2	1.138	1.256	0.224	0.638	0.472	2.61
35.	0.68	21.5	0.636	1.203	0.176	0.415	0.304	2.04
36.	0.68	22.2	0.752	1.047	0.173	0.362	0.279	2.98
37.	0.82	24.2	0.888	1.534	0.188	0.477	0.322	2.10
38.	0.63	31.9	1.286	1.557	0.254	0.645	0.442	1.36
39.	1.15	33.8	1.669	1.552	0.254	0.586	0.447	2.29
40.	1.29	24.3	1.075	1.026	0.180	0.337	0.251	1.45
41.	0.51	21.2	0.951	1.221	0.217	0.389	0.298	3.77
42.	1.07	19.6	0.611	1.196	0.137	0.356	0.262	1.20

TITLE: GUAYULE BREEDING EVALUATION FOR INCREASING RUBBER AND RESIN PRODUCTION

SPC: 2.1.03.1.b CRIS Work Unit: 5344-21000-002

INTRODUCTION

The commercialization of guayule (Parthenium argentatum Gray) depends on the development of cultivars with high quality and high yielding characteristics. Presently a wide variety of guayule germplasm is available to breeders and the means to generate more variability also exists. The next logical step in the guayule breeding program is to identify lines that are consistent in their quality and yield and to compare them in various types of environments.

Various projects have recently been established for this purpose. The longest standing is the Uniform Regional Variety Trial which was planted in October 1985. This same planting was also carried out in four other locations across the Western United States. The purpose was to compare promising guayule lines chosen by the Guayule Management Committee, and test their performance in different environments over a period of three years. In October 1986, 29 selections from the University of California, Riverside program was established in Maricopa, AZ. This same experiment was also planted in Riverside and Palmdale, AZ. Three years of harvest data will be obtained, beginning in February 1988, to evaluate these lines and estimate the genotype-environmental interactions. Two additional experiments were planted at Maricopa, AZ, in March 1988, to evaluate selections made from a cooperative effort with the University of Arizona. The purpose of one is to evaluate 16 selections in a replicated experiment. The second study included four selections comparing seed progeny and vegetatively produced plants. Since the plants produced vegetatively should be genetically the same as the plants used to obtain seed of the progeny, a parent-progeny comparison can be made in this replicated study. Information about the heritability of various guayule traits can then be obtained.

Harvest data up to the second year from the Regional Variety Trial is presented below. Data from other projects are not yet available due to the young age of the planting but will be available in subsequent years.

Field Procedures

The Second Guayule Uniform Regional Variety Trial was established in 1985 at five locations including Ft. Stockton, Tx, Rio Grande, TX, Las Cruces, NM, Riverside, CA, and Maricopa, AZ. Eight guayule lines being evaluated for this study were N576, 11605, N396, C250, C254, A2101, 11604, and 11634. These lines were examined for percent rubber and resin, dry weight (kg/ha), and rubber and resin yield (kg/ha). Samples from all locations were sent to Dr. Earle Hammerstrand, NRRC, Peoria, IL, for rubber and resin analysis by NIR method.

The study design was a randomized complete block with four replications. Plants were to be harvested each year for three years following planting and terminated after the 1988 harvest. For each harvest six whole plants in each replication were dug from the field and bulked as one sample. Fresh weights were taken of each sample. Plants were then chipped through a Diadem chipper to approximately 1/2" branch diameters. A sample of this was taken to determine percent dry weight by oven drying for 48 h at 50° C. The estimation of dry weights and yields were figured by assuming 27,500 plants per hectare.

Transplants were planted at the Maricopa location on October 8, 1985. The first year's harvest was in March 1986. Plants were in the ground less than six months at the time of the first year's harvest. Since the planting took place only a few months prior to this dormant season, plants were very small and little information about the varieties was obtained. The second year of harvest was in March 1987. Analysis of variance and mean separation were used to compare varieties and distinguish differences from these date (Tables 1 and 2).

Results

The first year's data showed significant differences in dry weights but no significant difference in percent rubber and rubber yield (Table 1). A2101 had at least twice the dry weight mean as the other lines but was the lowest in mean percent rubber. It still produced the highest mean rubber yield the first year although not significantly different than the others. As mentioned above, these plants were not in the ground more than six months prior to the first harvest and therefore these results are of little value.

The F values in the analysis of variance for the second year's data indicate significant differences between guayule lines dry weight, percent rubber, and rubber yield. Percent rubber and rubber yield were both significant at the .001 level and dry weight at the .01 level. The mean separations reveal which means are significantly different (Table 2).

A2101 was placed in a group apart from the other lines by this separation method. This line had the highest mean dry weight again the second year and also the lowest percent rubber as in the first year. However, in the second year the rubber percentage was much lower than any other line tested. This resulted in a lowest mean rubber yield. This is evidence that most lines examined so far with low rubber percentage do not compensate in yields even though they have more biomass. Beside the lower yields, these plants because of their size, are a problem harvesting and processing.

Lines C254, 11604, C250, and 11634 had the highest rubber yields and the highest rubber percentages for this location. The mean rubber percentage of this group ranged from 6.8% to 6.2% and were not statistically different. The mean rubber yield ranged from 919 to 774 kg per hectare for the four lines, also statistically the same. This is substantially higher than the line with the lowest mean rubber yield, A2101, with 501 kg per hectare.

SUMMARY

The evaluation of guayule breeding material is developing at a good pace. Although the results of only one of the four projects are presented here, much more information will be available to us as plants become old enough to harvest. the development and evaluation of germplasm for a breeding program take a great deal of time and consistent manpower to be successful. These current projects have been well planned and involve cooperation between researchers. The eight lines evaluated in the Uniform Regional Variety Trial indicate that after two years of growth, yields are approaching 1,000 kg/ha of rubber. The best lines for yield include C254, 11604, C250, and 11634. These yields are definitely improvements from the start of the program. Indications are that with continued efforts, the potential is present for further substantial increases in yields.

PERSONNEL

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TABLE 1

Regional Uniform Variety Trial
1986 1st Year

Means, standard error, and Waller-Duncan grouping for dry weight, rubber content, and rubber yield of 5-month old guayule plants at the Maricopa, AZ, location.

Entry	Dry Weight (kg/ha)		Rubber Content (%)		Rubber Yield (kg/ha)	
A2101	62.5 ± 17.4	A *	2.3 ± .20	B	1.50 ± .20	A
N576	42.0 ± 6.2	A B	2.9 ± .19	A B	1.23 ± .19	A B
11605	31.5 ± 1.4	B	2.8 ± .07	A B	0.90 ± .07	A B
N396	29.4 ± 7.1	B	2.9 ± .15	A B	0.88 ± .15	A B
11604	28.8 ± 4.5	B	3.1 ± .08	A B	0.90 ± .08	A B
11634	23.0 ± 1.6	B	3.0 ± .34	A B	0.70 ± .34	B
C254	21.6 ± 0.8	B	3.1 ± .22	A B	0.65 ± .18	B
C250	20.5 ± 1.8	B	3.2 ± .18	A B	0.68 ± .22	B

* Means with the same letter are not significantly different at the .01 level by the Waller-Duncan k-ratio test.

TABLE 2

Regional Uniform Variety Trial
1987 2nd Year

Means, standard error and Waller-Duncan grouping for dry weight, rubber content, and rubber yield of 17-month old guayule plants at the Maricopa, AZ, location.

Entry	Dry Weight (kg/ha)		Rubber Content (%)		Rubber Yield (kg/ha)	
A2101	16559 ± 1169	A *	3.0 ± .26	D	501 ± 73	D
C254	13565 ± 1098	B	6.8 ± .36	A	919 ± 103	A
11604	13362 ± 835	B	6.4 ± .28	A	861 ± 63	A B
C250	12981 ± 710	B	6.6 ± .17	A	860 ± 57	A B
11634	12458 ± 783	B C	6.2 ± .42	A B	774 ± 85	A B
N396	12091 ± 569	B C	5.7 ± .47	B	699 ± 88	C B
11605	11663 ± 628	B C	4.9 ± .32	C	573 ± 47	C D
N576	10415 ± 745	B C	5.7 ± .18	B	592 ± 60	C D

* Means with the same letter are not significant by different at the .01 level by the Waller-Duncan k-ratio test.

TITLE: AUTOMATIC CANAL CONTROL METHODS

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INTRODUCTION

A number of methods have been proposed for the automatic control of gates within canal systems. The purpose of this report is to attempt to categorize these methods in the context of control theory.

There are a number of standard control methods. Feedback control schemes measure output conditions and adjust the process input. Feedforward control schemes measure the input conditions and adjust the input (e.g., measure one input and adjust another input variable). Optimal control schemes determine the optimal input based on assumed conditions with no input or output measured. Optimal control is frequently combined with either feedforward or feedback control. Techniques used to implement these basic control methods can be subdivided into statistically based control and process based control.

STATISTICALLY BASED CONTROL

Statistically based control methods use statistical information about the process conditions (input or output) to determine whether or not the process is in control or out of control. Typically some acceptable tolerance on the level to be controlled is established. If the level is outside these control limits, adjustments to the inputs are made. These adjustments can be either empirical or can be based on results of prior evaluation of a process model. No process model per se is included in the feedback process. These techniques are usually designed to be very simple so that they can be evaluated in real time. They are limited in that they ignore relevant information about the physical process. For processes with a time delay between input and output, an empirical time delay is used to provide stability.

Statistical process control methods are almost exclusively feedback (as opposed to feedforward) and generally do not include an optimal control component. Examples of statistically based process control include acceptance sampling, time series forecasting, etc. Changes in input conditions are frequently handled by restarting the statistical algorithms, rather than correlating the new conditions with past output. They are applicable: where no process model exists; where a process model is too inexact or complex, for example when physical material properties are not known and too expensive to measure; or where real time constraints preclude evaluation of a complex process model.

Acceptance sampling will not be discussed here since it has little relevance to canal control techniques. There are a number of time series forecasting techniques that are relevant for canal control. The simplest scheme is to provide a control action when a single measured value is outside predetermined control limits. If time delays are significant, then this method may make adjustments too late. More sophisticated techniques attempt to determine whether the measured level is "headed" out of bounds. This is done by using a series of measured water level to predict future water levels. The problem here is to distinguish between random fluctuations in level and a trend away from the control setting. Time series forecasting techniques such as exponential smoothing are ideally suited to this type of problem. With these techniques, the only statistically based decision is whether a corrective action needs to take place. It provides no information on how much correction is needed nor on when to make corrections. These decisions are made prior to implementation of the technique.

Box-Jenkins techniques: Box-Jenkins methods are an extension of the simple methods such as exponential smoothing and moving averages. They provide more flexibility to model a wider range of statistical conditions. These methods have been extended to include correlation of output with prior input. This allows them to account for time delays in the process. SAS's State Space modeling is an example of this type of statistical model. However, it is actually more general in that it allows correlations of inputs and outputs in both directions. It is a true multivariate approach, analogous to the General Linear Model of classical statistics (e.g. hypothesis testing). As a result, the SAS state space approach is more cumbersome than needed for feedback control. The general form for Box-Jenkins type feedback models with a single output is

$$\Phi(B)y_t = \gamma(B)u_t + \Theta(B)\varepsilon_t \quad \text{.......................................(1)}$$

where

y_t = output at time t
u_t = input at time t
ε_t = estimation error at time t (random with mean of zero)
B = backshift operator, such that
$\Phi(B) = y_t + \Phi_1 y_{t-1} + \Phi_2 y_{t-2} + \ldots$

and $\Phi(B)$, $\gamma(B)$ and $\Theta(B)$ are vectors of constants. (Note that Θ is used differently in time series forecasting than it is used in functional model parameter estimation).

Kalman Filtering: Bayesian forecasting with Kalman filtering is a similar approach to Box Jenkins' in that state transition information is used. The major difference is that the Kalman filter explicitly considers process state information in addition to input measurements. Output is based on the current state (and inputs), while the current state is based on prior states (and inputs). Errors in output estimation are separated from errors in state transition estimation. The resulting systems of equations for both these models are all linear. The Kalman filter is potentially more useful for feedback control applications than a strictly state space formulation. The Kalman filter statistical forecasting model is sometimes referred to as the Dynamic Linear Model. (This is different from the General Linear Model which is used for hypothesis testing, e.g. ANOVA). The general form of this model for a single output variable y_t is

$$y_t = F_t S_t + v_t$$

$$S_t = G S_{t-1} + w_t \quad \text{...(2)}$$

where

S_t = state vector at time t
v_t, w_t = estimation errors at time t (random with means of zero)
F_t = transition vector between current state and measured output
and G = state transition relation (can be fixed or a function of time).

On the surface, equations 1 and 2 appear radically different, however in actuality they contain much of the same information, just in different forms.

Use of statistically based methods assumes a period of time over which the system is observed. These observations are then used to develop a statistical model of the process. If the process is linear, standard procedures are available to determine feedback control settings. If the process is not linear, then it can frequently be (locally) linearized in order to use these relatively straightforward techniques. If the linearization is not adequate, then solution methods become much more complicated, as does control. Development of these models is very much an art. As a result, the simpler, less powerful methods are most often used since they require less data and development time. Simulation can also be used to develop reasonable statistical models of a process when feedback is used.

The statistically based models discussed here are referred to as parametric models. That is, a model is constructed with a series of parameters which when multiplied by a series of constants gives a forecast. The form of the model does not change during the forecasting process. Parametric models nearly always assume that model errors are normally distributed and random. This assumption is used to 'fit' a model to a data set (e.g., by least square difference).

It is also possible to construct a nonparametric statistical model to provide feedback control. Nonparametric models do not assume a particular equation form. There are two groups of nonparametric techniques in common use: acceptance sampling methods, such as the Runs Test; and nonparametric regression. Common nonparametric regression techniques include the nearest neighbor estimator and the kernal estimator. Nonparametric regression methods may not be very applicable to process control, since they tend to 'over fit' the data. Nonparametric regression is a fairly new field. Most nonparametric models assume 'random' model errors. Statistical pattern recognition methods are nonparametric in nature and may have some application in statistical process control.

Adaptive estimation: In the development of parameter and control extimates, a model is constructed so that errors are normally distributed with a mean of zero. The process underlying this model is assumed to be stationary with respect to the model, that is model parameters are not time dependent (even though actual values of input and output are time dependent). There are some processes which exhibit sudden shifts in process conditions which make the stationarity assumption invalid. Adaptive techniques are used to revise the process model based on information that suggests a shift in process conditions. A model for a process is usually developed off line over a 'tuning' period and then applied to current and future time periods. Under adaptive control, 'tuning' continues to take place on-line. In some cases, the process gradually shifts away from the process model, in which case, the parameter estimates can be gradually shifted with some form of statistical averaging. Or as an alternative, the model parameters can be periodically reviewed and undated, although this might not be considered adaptive estimation or control. In other cases, the process makes rapid (step) changes. This may require a sudden change in parameter values to keep the system under control. This can be a difficult control problem, since it requires both the detection of a sudden shift and determination of new model parameters based on limited data. Current methods available for quickly adjusting for rapid shifts tend to be ad hoc rather than theoretically based (e.g., try something and see if it works).

PROCESS BASED CONTROL

Process (or functional) model based control methods use a mathematical model of the physical process to determine any adjustments to the input required to bring the output to the required condition. Process based control methods often include an optimal control component. Under pure optimal control, process conditions are assumed and the optimal control settings are determined from the process model. In general, it is not possible to predetermine all process conditions and states a priori. Thus some feedback of process conditions (either input or output) is usually necessary for optimal control to be effective.

Process models represent the physical dynamics of the process involved. They are constructed to compute the results (output) for a given set of physical conditions (inputs and states) over time. Unless the model is very simple, it may not be possible to directly solve for the inputs needed to arrive at a desired process output. In addition, there may be several combinations of inputs and states that result in a common output state. There are two basic approaches to determining optimal control settings for some desired output. First, the process model can be run multiple times and response surfaces developed which can be later evaluated. If this is infeasible (e.g. due to large number of possible surfaces) search methods can be used to find the optimal input states. The second method is to linearize the dynamics of the problem so that a linear relation exists between inputs, states and outputs. Then optimal input conditions can be determined directly from desired output. In practice, this is slightly more complicated since inputs and outputs are related by a linear system of equations rather than a single equation.

Incorporating optimal control within feedforward control requires little modification to the above discussion for optimal control, since input is assumed known initially. The only modification would be associated with possible errors in input measurements. If the response is symmetric and the errors are normally distributed, then the expected (measured) value of the input will give the expected (computed) value of the output. In this case, measurement errors do not affect the optimal control setting. If these assumptions do not hold, then the expected value of the output must be computed as a random variable, a somewhat more time consuming process.

Incorporating optimal control into feedback control is less straightforward. For example, what if the optimal control setting does not produce the desired output. This could be caused by errors in input and output measurement, errors in the process model, or errors in the initial process state. Recognizing the possibility of these errors, feedback control models are concerned only with <u>relative</u> changes in conditions, not absolute conditions.

<u>Classical Feedback Control</u>: Classical feedback control techniques are based on Linear Systems Analysis (LSA), in which the process model is reduced to a set of linear ordinary (as opposed to partial) differential equations. Laplace transforms are used to represent these linear differential equations as linear equations. These linear equations are then combined, and a single linear relation (transfer function) is determined for the process and any feedback. Inverse Laplace transforms are used to develop an expression for total system response to input. In order to determine inverse Laplace transforms, the transfer function denominator must be factored so that the transfer function can be broken out into partial fractions. The coefficients of these partial fractions are a complex combination of the variables that existed for the process and the feedback control. The approach taken in LSA is not to determine optimal control settings, but rather to follow simple rules based on the error in the desired output. This implies that the response to control changes are immediate (i.e., no time delay).

There are four simple classical control techniques; proportional control (P), integral control (I), differential control (D), and on-off control. Under proportional control, the input is directly proportional to the error in the output. Under integral control, the input is proportional to the integral of the error (area under time-error curve, or summation of error values). Under derivative control, the input in proportional to the rate of change of the output. Under on-off (or bang-bang) control, the input is either on or off depending on whether the error is positive or negative. These control methods have found many applications. In many cases, analog electronic hardware is available for performing the feedback control function. PID controllers are a fairly common, robust control method for many applications.

Application of PID controllers requires evaluation of the proportionality constants (gains) for each component (P, I and D control).

Linear Systems Analysis is used to determine the effects of these proportionality constants on the stability, response time, overshoot and oscillatory behavior of the system. Thus control gains can be determined which will provide a particular level of performance. The system response depends on both the dynamics of the system and the PID control gains. In application, only feedback gains are used in control. LSA is used to evaluate the response of the control system prior to operation. In the LSA evaluation process, coefficients are determined for an output response equation based on assumed system behavior and feedback gains. These coefficients combine the effects of the system behavior and the feedback control behavior. Time lags between input and output result in oscillatory behavior of PID controllers. The greater the time lag, the greater the magnitude and period of the oscillations. This problem with classical PID controllers has prompted the development of control algorithms that include predictions of process changes and delays.

If the process is not well known beforehand, it is possible to set the feedback gains by observing output performance changes resulting from input changes. A "tuning" period is used to determine proper feedback gain levels to give a "reasonable" response. Exact determination of feedback gains is not possible under these conditions because it is not possible to separate the effects of unknown process parameters from controller gains. Determining system response relations from observed output is frequently known as the identification process. Usually some form of response relation or model is hypothesized and the identification process then determines values for the model parameters (also known as parameter estimation). It must be remembered that these parameters are neither system dynamics variables nor feedback gains, but a combination of the two.

Regulator Theory: Regulator theory provides a significant improvement in control capabilities over traditional Classical control methods (Åström, et al 1977). These methods have been available for several decades, but have found their way to general application only in the last 10 to 15 years. Under regulator theory, the feedback control system is subdivided into three parts. The first (parameter estimation) determines values of true process variables strictly based on feedback from the process. The second determines values for control parameters based on process parameter estimates and their uncertainties. The last uses control parameter estimates and output measurements to determine actual control settings. This separation of system parameter estimation from control parameter estimation provides for a wide variety of methods.

If the process is linear, there are a number of techniques which can be used in parameter estimation. The most common are based on least squares (error) estimates and maximum likelihood estimates. When the process is linearized over time, the process equation form is essentially identical to the stochastic time series equation, Equation 1. Thus the process model can be derived from true process dynamics or from statistical estimation. The resulting model is essentially the same. Unfortunately, the process model must be strictly from process dynamics (theoretical behavior) or from statistics (observed behavior). Combining the two is somewhat difficult, and will be discussed later. If the process is not linear, then the state transition relations of Equation 1 are not usable. Here, search procedures are generally required in order to determine values for true system variables. In some cases, it may be possible to use some pseudo system response in place of true process variables.

Control strategies (laws) can be developed which are in the form of a linear transfer function, for example (Åström, et al, 1977)

$$u_t = \frac{G(B)}{F(B)} y_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where u_t is the control action. If it is desirable to minimize changes in input, then Linear Quadratic Gaussian Theory can be used to generate control laws based on minimizing the expected value of the sum of the output error squared and a constant time the control change squared. The control law developed is based on a known linear process model of the form of Equation 1. Control laws can also be generated which simply minimized the expected variance of the output (i.e., regardless of number and amount of control changes), again based on a known process equation (minimum variance controllers).

In observing Equation (3), it is clear that control laws could be generated from statistical observation of the impact of control changes for a given set of circumstances. It may be difficult to generate such control laws without a significant number of trials, many of which would have undesirable outcomes. One method for overcoming this undesirable feature of generating statistically based control laws is through the use of genetic algorithms. Genetic algorithms are a technique for varying the control settings from the current best estimate of the optimal control setting in order to work toward a better estimate of the optimal control setting.

Kalman Filter: The Kalman filter was described above according to its use in statistical estimation. However, it was originally develop as a means of parameter estimation for process model based control. The equation form is given in Equation 2. The only difference in application for functional or process based control, as opposed to statistically based control, is that the state transition matrix G and the transfer function F_t are process model based rather than statistically based. As discussed above, the state transition approach of the Kalman filter has advantages over the state space approach of regulator theory. The Kalman filter approach can be used to generate control strategies as well as parameter estimates.

Adaptive Control: The same basic principles of statistical adaptive control apply to functional model adaptive control, namely that if the process is not stationary with respect to the process model, adaptive control becomes necessary. Adaptive control laws, even for functional model based control systems, are statistically based, since it is necessary to determine 'statistically' if a shift in the process has taken place. Åström (1983) presents three type of adaptive control which are in use. Gain scheduling uses measured values of auxillary variables to adjust model parameters. This requires the auxillary variable to be correlated with changes in the process. Model reference adaptive control (MRAC) uses a process model to predict process outputs. (Note that an actual process model is not used in linear control theory. It is however embeded into the estimation and control process). MRAC uses the errors between the predicted and actual output to adjust model parameters. Methods for making this adjustment while still assuring stability and convergence are not easy to develop. Current methods are somewhat limited. Self-tuning regulators use recursive parameter estimators to essentially reevaluate model parameters in real time. A number of different types have been developed, most are based on a statistical evaluation, for example maximum likelihood estimation or least squares. (The self-tuning regulator was first suggested by Kalman in 1958).

Nonlinear Process Control: Many real processes are nonlinear in nature. Use of the above techniques requires linearization of the process (differential) equations. The most common approach is approach is local linearization. For the classical control theory, this can lead to computational inefficiencies if the entire set of equations must be resolved for each set of conditions. Regulator theory and Kalman filtering essentially resolve for local conditions anyway, so this poses no significant increase in computation time. Solving nonlinear parameter estimation problems without linearization pose a much more difficult problem. In general, response surface search methodologies are employed. Such methods can be extremely inefficient and time consuming computationally. Development of control strategies for nonlinear systems can also be very difficult. Normally, parameter estimation provides a mean value and a standard deviation based on a normal distribution, which is symmetric. For a linear system, a symmetric distribution on input gives a symmetric distribution on outputs. Then the optimal control can be based on the mean parameter value. If the response in nonlinear, then the symmetric input distribution does not result in a symmetric output distribution and the optimal control setting may not result from the mean parameter value. This greatly increases the computation time needed to find optimal control settings.

In some processes, the final output (upon which performance is based) is not observed until the process has been completed. This is particularly true for batch jobs, as opposed to continuous processes. In this case, intermediate information about the process is monitored as a means of determining the state of the system. Such situations strongly suggest the use of functional, as opposed to statistical, models of the process. In some cases, hierarchical control would be in order, where the low level controller would maintain the intermediate output at the desired level and the higher level controller would determine the appropriateness of the desired level used by the low level controller.

FUZZY AND EXPERT CONTROL

Many complex processes are too vague to be precisely controlled by modern control theory methods. Many such systems are controlled by qualitative, ad hoc rules for control. Fuzzy control systems attempt to qualitatively determine the state of the system, from which control rules can be developed. These control rules are generally developed from first observing an "expert operator", then observing and adjusting the control rules according to observed performance. (This can also be done statistically, for example with genetic algorithms). Fuzzy system theory provides a systematic and mathematically rigorous method for solving these type of control problems. In many ways, this is similar to the Expert System approach, where the control rules of an expert operator are encoded. On a preliminary level, both provide essentially ad hoc control rules common to many mannually controlled systems.

CANAL CONTROL METHODS

There are a number of control strategies which can be employed in the control of canal networks. A significant distinction is made between the control of in-line canal check gates for controlling water levels and flows within a canal and the control of canal offtakes where water is transferred from one canal to another. The basic control strategies are outlined below.

Upstream control: Each inline check gate is controlled so as to maintain a constant water level immediately upstream, where offtake gates are typically located. By maintaining a constant level on the upstream side of an offtake gate, it is presumed that offtake flow is constant. Errors in rate of flow from upstream canal reaches are simply divided between the continuing canal downstream and the offtake. If offtake structures are designed to maintain constant discharges, errors tend to accumulate downstream. These system can be extremely stable, since there is essentially no time delay involved.

Downstream control: Each inline check gate is controlled to maintain a constant level at some point downstream. If the level to be controlled is at the downstream end of the next canal reach or pool downstream from the gate then a significant time delay exists which must be taken into account by the control system. In addition, the distance may be great requiring some form of communication (e.g., other than water). If the level to be controlled is immediately downstream from the reach time delays are eliminated, but a number of other problems result. Different flow rates in the reach result in different water surface profiles. Thus a constant level at the upstream end of a pool does not correspond to a constant flow rate at the downstream end of a pool. To allow zero flow in the reach requires a canal with a level top which can be prohibitively expensive for all but very small canals. In addition, any change in flow to adjust level results in a wave which travels to the downstream end of the reach, causes changes in flow there and generates a reflective wave which travels back upstream. In addition, changes in backwater curves can eventually change the level at the upstream end of the reach. The result is a slow oscillatory behavior. In actuality, the level at any point in the pool can be used as the desired level for control. If the level to be controlled is in the center of the canal reach, then the control method effectively becomes a controlled volume control.

Flow Rate Control: Flow rate control is a method for regulating the discharge at canal bifurcation and offtakes. Here an offtake gate is regulated to remove a constant discharge from a canal, independently from either upstream or downstream levels.

Centralized Control: Upstream, downstream and flow rate control are essentially local control methods, where control of a particular gate is dependent strictly on the conditions in adjacent pools. Centralized control methods attempt to coordinate the regulation of all (check) gates for a particular canal. There are a number of strategies which are employed and will be discussed below.

CANAL FEEDBACK CONTROL

A number of mechanical/hydraulic devices are available for the control of local canal water levels and flow rates. Most have been reliable and stable and will not be discussed in detail here. Of note, however, is the misapplication of some of these local controllers for trying to control the water level immediately on the downstream side of an offtake gate, when in reality the level at the downstream end of the pool needed to be kept at a constant level. The basic problem was discussed above.

The use of motorized gates for canal control has introduced an additional problem. Motorized gates tend to move much more quickly than water levels and flows can respond. Thus even for local controllers, delays have to be built into the system to avoid unnecessary oscillations. Two approaches to this problem are: the use of variable speed stepper motors, and the use of variable on-off times. For the size motors required for canal gates, stepper motors are probably prohibitively expensive. The later method with short on times followed by longer off times (even when control action is requested) is more common. Without such delays and a control deadband, motors would be quickly worn out.

EL-Flow: One of the first applications of true feedback control of inline canal reaches was the EL-FLOW system developed by the U.S. Bureau of Reclamation in the late 1960's and early 1970's (Ploss, 1987). EL-FLOW is a local downstream control system, where the water level at the downstream end of a reach is feed back upstream to the gate controlled. EL-FLOW was developed with classical control techniques as a proportional controller. It has been implemented in analog form on the Corning canal in central California. Much of the mathematics associated with the development of the control system can be found in Shand (1971). Since classical control does a rather poor job of handling time delays, some modifications to classical proportional control were evaluated.

As discussed previously, Classical control techniques are concerned with relative changes (e.g., relative gate position). When time delays exist, errors in control persist even after the correct amount of corrective action has been applied. To avoid this problem, the EL-FLOW system uses absolute gate position as related to control error. (thus this becomes proportional-position control rather than classical proportional control). This provides the initial adjustment required for downstream flow changes. However, this provides a constant gate opening for any downstream water level. To overcome this, the RESET function was added, which integrates (accumulates) errors in water levels. EL-FLOW is essentially a type of PI controller. The constants must be carefully chosen so that the proportional controller will not initiate too large of a control action, and such that the reset function will not correct too soon or too much. Such constant were developed from extensive computer simulations of the canal response and through experience on the Corning canal itself. Deadbands of roughly ±30 mm were used to limit gate cycling.

The EL-FLOW system is primarily suited to the control of main canals with slow and gradual flow changes and a narrow range of conditions. Control of more dynamic canals with EL-FLOW is likely to be unsuccessful. While the control algorithms are fairly simple, the proportionality constants require extensive evaluation. Thus EL-FLOW is unlikely to become a widely adapted procedure for canal control.

BIVAL: BIVAL is a local controlled volume downstream control method. It utilizes water levels from both ends of the canal reach downstream from a structure. A wieghting coefficient is used to average the two depths. The measurement of a depth immediately downstream from the control gate helps to offset the problem of response time to the downstream end of the pool. A wide deadband is required to provide for stability. The control of the water level in the center of the pool requires only the lower half of the canal reach to have a level top. BIVAL has primarily been applied to very large canal/river systems, and is typically operated manually. Gate adjustments are made at prescribed time intervals and by prescribed amounts, both determined empirically from detailed hydraulic modeling. Typical deadbands are ±50 mm. BIVAL is primarily applicable to large, slowly responding canal/river systems. Its application is limited similarly to EL-FLOW.

Gate Stroking: Gate stroking is a method of optimal/feedforward control of all gate settings in a large canal. It is based on maintaining a constant volume in each pool. Thus it is a global (centralized) controlled volume upstream control method. Earlier studies on canal transients indicated that simultaneous control all gates minimizes transients. It is based on prior orders for water, as is upstream control, as opposed to downstream control which is meant to accommodate changes in downstream demand. Gate stroking attempts to accurately model the canal hydraulics prior to operations. It uses hydrodynamic models to simulate canal flows and route flow changes through the canal reaches. It requires fairly exact modeling of canal and gate discharge behavior in order to properly determine gate settings. As such, it takes continual monitoring of canal response and adjustment of parameters. In addition, it is not responsive to changes in demand. Any real-time changes in flow from the feedforward output must be done manually. In practice, the complete solution of the unsteady flow equations becomes unwieldy. Gate stroking represents an improvement on manual upstream control, but does not provide the flexibility of the various downstream control techniques.

Dynamic Regulation: Dynamic regulation is basically a centralized feedforward optimal downstream control method, although feedback is also used. Expected demand for water is evaluated at the downstream end and accumulated back toward the head of the canal. It does not attempt to keep water levels exactly constant, nor does it attempt to maintain constant pool volumes. The system is dynamic in that it allows the controlled volume of each pool to vary. The large freeboard requirements of controlled volume control and BIVAL are essentially eliminated. The system uses information from previous simulation studies to determine relationships for velocity as a function of head and discharge. Thus under real time control, simple backwater calculations and routing methods can be used to simulate gradually varied flow. Like gate stroking, it relies on good estimates of canal and gate flow conditions. Feedback of actual and predicted water demands are made ten times per day (water orders are arranged). Feedback of water levels and subsequent control actions are made every fifteen minutes. Operation of such a system requires a considerable engineering effort. It would not be expected on any but large canals.

One feature of Dynamic regulation makes it particularly attractive. In many canal control situations, downstream control is not feasible since control over the supply is not allowable. Supply flows are generally governed by some form of flow rate control, which for control of the remainder of the canal is essentially upstream control. Dynamic regulation suggests the possibility of starting with upstream control at the head end and progressing to downstream control at the lower end. Mismatches between supply and demand can be accommodated with canal storage changes.

Zimbelman's Method: Zimbelman's method is a statistically based feedback control technique. While the control algorithms are locally based (i.e., each gate adjustment is determined independently), it is operated as a centralized control system. It uses time series forecasting methods to determine if and when the water level at the downstream end of a pool will move outside the deadband range. The idea is to make corrections to gate settings prior to the level going out of control. This technique is useful for adjusting for random variations in conditions or for gradually varying flows (e.g., slight mismatches between inflows and outflows). The travel time between checks is partially accounted for by forecast horizon. For example will the water level move outside the control band before the effects of an adjustment in the upstream gate will reach the downstream end of the pool? The amount of adjustment to be made must be developed from simulation studies or field trials for a particular canal. The control algorithm must also consider the speed of gate movement (or delays in control once a control action has taken place). Once the control level is no longer moving away from the desired level, control actions stop. With properly chosen constants, the system should be very stable. A typical deadband was ±60 mm. In addition, some information on average water surface slope is needed. This method is better applied to larger canals, but with good selection of empirical constants it should be applicable to fairly small canals as well.

Two new canal system were constructed in Arizona between 1986 and 1988 which were designed for use with Zimbelman's control method. Deliveries will be arranged with farmers, but canal levels will be controlled as if the system were on demand. Excess capacity was built into the upstream most reach to accommodate mismatches between supply and demand. The supply is at a controlled rate, but can be changed every 15 minutes.

CARRD: One of the problems with applying canal control methods is errors in water level measurements. EL-FLOW used electronic filtering to get better water level reading, Zimbelman's method used smoothing techniques. Burt (1982) used multiple water level readings along a canal reach to establish the downstream level. The CARRD system developed from this approach has some of the advantage of BIVAL in that measurements close to the controlled gate can be included. CARRD uses linear regression on a series of water levels to establish an estimate of the projected downstream level. Both the projected downstream level and the true downstream level are used in the control logic. CARRD was able to get by without having an empirical time delay by using slow gate movements. In some ways, CARRD's logic is similar to Zimbelman's method. Rate (or amount within specified time) of gate movement is dependent upon how far the controlled level is from the target level and in which direction the water level is headed. In initial studies, three rates of gate movement were used. Rates of gate movement, deadbands, etc. are empirically determined. CARRD resembles a fuzzy controller, since controls are based on arbitrary rules based on ranges of particular variables.

Linear Quadratic Regulator: None of the above methods can be classified as functional model based feedback control. Both Reddy (1986) and Bologun (1985) used linear quadratic regulator theory to develop feedback control algorithms for inline check gate control based on maintaining a constant controlled volume. Solution required linearization of the Saint Venant Equations. This is reasonable so long as conditions are changing slowly, e.g. in large canals. Reddy found that when conditions change significantly, as in small canals, the linearization and subsequent control resulted in significant errors. These errors should be progressively reduced as the system approaches an equilibrium condition. Assumptions regarding canal hydraulic properties are also required. In this case the requirements are not as strict as with feedforward methods, although errors in estimates of variables can cause non-optimal performance. For example, roughness is generally given as a known parameter. For measured values of gate opening and flow depth, a discharge can be estimated from the linearized equations. This discharge then enters into the feedback control equations. The effects of roughness and discharge may be different in the parameter estimation relations than they are in the control relations. Thus an error in roughness would cause an error in discharge prediction. While this error is not serious in itself, to could result in poor control.

Regulator theory holds the most significant promise for a general control technique. Several unanswered questions remain. First, under what conditions is the linearization of the Saint Venant equations reasonable? What effect will changes in hydraulic properties have on control performance? How can the control algorithms be altered to provide for control of downstream level rather than volume? The methods presented to date can control each pool with local controllers or can control a series of reaches.

SUMMARY AND DISCUSSION

The various control methods can be classified as shown in Table 1. EL-FLOW and BIVAL are essentially limited to very large, slowly changing canals. Gate stroking, being essentially a feedforward method is also limited to fairly large canals because of the engineering effort to precisely model conditions. It is also computationally cumbersome, and may find limited application. Dynamic regulation has similar limitations in that extensive engineering evaluation is required. These latter two methods do not actually use process control algorithms, but use actual, predictive process models. Use of such models does represent a technique used in nonlinear control, and so these are included under modern control methods.

CARRD and Zimbelman's method were both developed for use on relatively small canals. Zimbelman's method is more statistically based, while CARRD applies more ad hoc control (fuzzy) rules. As with most control methods, both require a 'tuning' period to adapt them to a given canal. LQR theory can significantly reduce this period of tuning without much engineering evaluation. It's range of applicability is still to be determined, (e.g. how reasonable is the local linearization and the state (discharge) estimation).

The methods in use consist of Classical control, statistical (stochastic) control, modern control (e.g., LQR) and to a certain extent Fuzzy control. Adaptive control has not at this time been suggested. Changes in conditions are so gradual in the large canals that have been modelled to date that this level of sophistication is not warrented at this time.

Both local and centralized control systems have been suggested. While localized algorithms appear more tractable, some form of centralized coordination also appears to be in order. Periodic review controllers, such as Zimbelman's, allow such coordination to take place, while still allowing simple local control rules.

Since most of these techniques have been applied to large canals that operate essentially continuously, very little attention has been paid to start up procedures. For smaller, intermittantly operated secondary or lateral canals, start up and shut down operations may become a significant consideration (e.g., it may not be desirable to leave the canals full when no demand is on the system).

To date no control methods have addressed the real world problem of the possible need for varying the control objective over the length of the canal, e.g. upstream control at the head changing to downstream control at the tail end of the system.

New Canal Control Scheme: Very few canal systems actually allow water on-demand any time a user desires. More typical is to arrange ahead of time when an irrigation delivery is to start. This allows the system time to respond to flow changes. With upstream control system, the lead time required on orders may be as long as it takes to route the water from the source to the farm turnout. Storage within the system, both in canals and reservoirs, is typically used to shorten these lead times. Purely downstream control methods preport to minimize these delay times by transfering a need for water at the downstream end of the pool immediately to the gate upstream. Travel time for a change in flow in the system is supposedly minimized to the time required for a flow change to travel through one canal reach. There are situation where this would not result in acceptible performance.

Consider for example a canal with five reaches operated under downstream (feedback) control with manually operated offtake gates. Water is currently being withdrawn from reaches 2, 3 and 5. Reach 1 is very long and reach 2 is very short. A new request for water comes from reach 4. The turnout gate is openned and water is withdrawn. The level in the pool drops. Flow to reach 5 is decreased. The gate at reach 3 opens dropping the level in reach 3 and subsequently the flow to reach 3 offtakes drops. This process is cascaded upstream. Even though storage from reach 3 is being used to fill the demand in reach 4, reach 2, 3 and 5 deliveries suffer not just until flow rate into the system is restored, by until all the canal storage volume is replaced. If offtake gates are automated for constant discharge, this problem is minimized. Upstream (feedforward) control systems attempt to minimize this type of disruption by routing flow through the canal based on known demands. Such systems are susseptible to errors in flow which tend to accumulate downstream.

Having to order the start time for a water delivery is not as restrictive as having a fixed irrigation duration, rate or frequency. It is not likely that many existing canal systems will convert to total demand deliveries. Even closed pipeline systems such as in the Westland Irrigation District do not allow random start ups. This logically leads to the possibility of a combination feedforward/feedback system, but not in the traditional sense. If a known change in delivery is scheduled to take place, routing can be used to supply the known change in flow through the upper reaches of the canal. Once that flow change has reached its destination, control can revert to downstream control. This allows the advantage of getting the flow to the destination with less disruption to other users, but at the same time minimizes the tailender problem. It also allows the users to alter their deliveries by cutting off early or late or by increasing or decreaseing flow by modest amounts without significant impact on other users. Earlier, a system which changes control algorithms with distance along the canal was suggested. This scheme suggests a change in control algorithms over time. This makes it somewhat of an adaptive control method.

The scheme would work like this. Suppose the system were operating under downstream control. A delivery is scheduled for reach 4 at 10:00 a.m. Routing shows that in order to get the flow to the turnout in reach 4 by 10, water would have to be diverted from the source by 5:00. Thus the headgate would revert from downstream control to upstream control at 5:00. (Leaving control of the pool level in reach 1 uncontrolled). This wave would reach check 1 by 7:30, therefore, check 1 would revert to upstream control, and so on down the canal. By 9:00, the flow would reach check 3, converting it to upstream control. By 10:00, the wave would reach the desired turnout. At this point, control would have to be converted back to downstream control. It is not clear at this time whether that would be done simulataneously for all reaches, whether it would start at reach 4 and proceed progessively upstream, or start at the diversion and move progessively downstream behind the wave.

There are several problems with this scheme that can probably be delt with satisfactorally. First, there is a period of time during the transition from one control scheme to the next where no control is exerted on certain water surfaces (as in example above). Second, any unsceduled changes in demand during the time where upstream control is in effect will not be accounted for until the system reverts back totally to downstream control. And finally, for large, flexible systems, there may always be a flow changes downstream, meaning that the system will never revert back to downstream control. The first problem can easily be solved by not converting totally to upstream control (e.g., gate position is determined by a weighted average of upstream and downstream level errors), and providing safegaurds to convert control if a level deviates too much. The second problem is somewhat more difficult. The routing can provide expected conditions and significant deviation from these conditions can be adjusted for by changing inflow rate, for example. The third problem can be easily solved by only converting to upstream control when the flow changes are significant in terms of canal reach volume changes during the reach transmission time. Or if a scheme for partial upstream/downstream control can be worked out, this can be solved by changing only partially to upstream control.

These types of strategies open up a new set of possibilities in canal control.

PERSONNEL A.J. Clemmens

Table 1. Classification of canal control methods.

	Feedback		Feedforward
	Local	Centralized	Centralized
Classical	EL-FLOW		
Statistical	Zimbelman CARRD BIVAL	Zimbelman	
Modern	LQR	LQR	Gate Stroking Dynamic Regulation

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TITLE: CANAL SYSTEMS OPERATIONS PROJECT

SPC: 1.3.03.1.d CRIS WORK UNIT: 5344-13000-001

INTRODUCTION

The phenomena under investigation in the canal systems operations project are the hydraulics and management of networks of small canals used to deliver irrigation water to the farm gate. Rapidly changing demand conditions combine with the complex free-surface hydraulics of open channels to make steady flow conditions very rare. Yet steady, known flows delivered on demand are required if farmers are to attain the full potential of on-farm application systems, or take full advantage of agronomic and market conditions. Thus while delivery agencies have an incentive to increase the flexibility of their scheduling policy to benefit farmers, increased flexibility tends to cause flows to be less uniform and predictable. Resolution of this conflict is the principal goal of the project: to provide the structural and algorithmic tools required to design, operate, and rehabilitate canal networks to allow flexible, uniform flows of irrigation water to the farm.

At the conclusion of its third year, the project has yielded an enormous amount of information on the operations of several canals in two irrigation districts. In 1987, project accomplishments included installation of a monitoring system along more than four miles of a lateral canal, statistical modeling of flow nonuniformities, and initial quantification of the effect of nonuniform flows on on-farm operations. Canal networks at the farm interface level have been shown to be complex systems which resist standard methods of statistical analysis. Yet the evidence is clear that irrigation deliveries are frequently not uniform and that such unpredictable flows make estimation of the performance of on-farm application systems difficult.

Wellton-Mohawk Canal Monitoring Study. Data collection continues in the Wellton-Mohawk Irrigation and Drainage District (WMIDD) in southwestern Arizona. The WM17.0 lateral, instrumented for intensive monitoring in 1985, continued in 1987 to provide detailed information on the operation of that three mile-long section of canal. An additional turnout (WM17.0-2.1L) was brought into the monitoring program in July. Two identical flumes were placed in the farm ditch on the north and south side of the turnout, with a single teed bubbler line for both. When a delivery is made, the bubbler at the flume in the direction the delivery is occurring has slightly less head above it than the bubbler above the ponded flume. The bubbler with less head will operate and allow measurement by the data logger. There were few equipment failures along the WM17.0 in 1987 compared to previous years, as we became adept at trouble-shooting instrument problems. District maintenance activities occasionally broke bubblers and in one instance broke a pre-cast concrete flume. Few problems persisted more than the three weeks between regular site visits to collect data and replace batteries.

A second lateral in the WMIDD was instrumented for monitoring in 1987. From March to April, fifteen measuring flumes were designed, constructed and installed along the M42.9 lateral both at farm turnouts and in-line lateral sites. The flumes were constructed of three-quarter inch plywood with structural support provided by perforated steel angle. Pieces were bolted together and secured to the canal with concrete anchors. This type of construction proved to be fairly simple, and a two-man crew could install all but the largest flume (capacity 90 cfs). From April to June the rest of the monitoring equipment was installed: fifteen instrument sites each with data logger and bubbler/transducer valve-switching gear to measure up to seven water levels or flow rates. Calibration of the double-bubblers and zeroing of the flume bubblers continued into early July when data collection began. Equipment problems were for the most part routine, although at several sites a second air pump had to be added to supply deep bubblers. The M42.9 is a much larger, longer lateral than the WM17.0 and is expected to show considerable contrast in its operation and performance.

<u>Wellton Delivery Uniformity Study</u>. Data from the WMIDD canal monitoring project were analyzed in 1987 to determine the sources of flow nonuniformities at the farm turnout and their relative magnitude. Deliveries made to the nine farm turnouts instrumented along the WM17.0 from July 1985 through June 1987 comprised the basic data set. It had originally been intended that in-line flows measured into the WM17.0-0.6 sublateral, and past the WM17.0-3.0 check structure would also be used to estimate flows at the farm turnouts downstream of these sites. But analysis indicated that these flows had different uniformity characteristics than actual turnout flows and were thus deleted from subsequent analyses of deliveries.

The original intent of analysis was to relate some measure of flow uniformity (dependent variable) to a number of presumed sources of flow variability (independent variables), and perform a multiple-regression or ANOVA type of statistical analysis. Significant sources, once identified, could then be examined with the goal to improve delivery flow conditions. Unfortunately, this approach proved largely intractable due to the complex interactions among system components (hydraulics and operations) and the observation type of measurements (as opposed to traditional experimental design). Standard statistical analyses also rely heavily on assumptions of independence and normalcy among variables, and these assumptions were largely unmet by the farm delivery data set.

The variable used to represent delivery uniformity was the coefficient of variation, cv, of ranked flow rate measurements accounting for 98% of the delivery volume. Values of cv ranged from 0.01 to more than 0.50, but most deliveries had a cv of less than 0.15; the 0.01 to 0.15 range included very good to very poor deliveries, and seemed not to provide sufficient detail to easily discriminate between good and poor deliveries. The 98% volume criterium was established by Clemmens and Dedrick for a previous study and is intended to discount undue influence of the few small flow measurements at the start and end of a delivery. The coefficient of variation did have some predictive power, as the results discussed below show. Further work is required to show that cv_{98} is indeed neglecting only the tails of a delivery, and to suggest other possible measures of uniformity. One candidate might be a cumulative volume statistic based on differences between actual and desired volumes throughout an event.

The independent variables thought to be sources of non-uniformity dealt with the circumstances of the delivery (lateral busy or rarely used, day or night, cropping patterns, cultural practice patterns), hydraulic conditions (flow rate, duration, concurrent deliveries, fluctuation in the main canal level, distance downstream of lateral heading, location within a pool), and the operator (regular or relief ditchrider). Some, such as variables SITE (delivery location) and SEASON (time of year) were found to explain significant portions of flow variability, but are too vague to relate to useful operational parameters. Better describers might relate to turnout type and condition, area served by turnout, current frequency of delivery along the lateral, or current volume per some time period. The number of deliveries concurrent to one being observed would seem intuitively to impact uniformity, yet use of this variable produced only ambiguous results. The measure of these effects might be improved by including as variables the location of the concurrent events, their relative flows and durations, perhaps others. Any further statistical work with data of this type will require more precise estimates of the sources of nonuniformity than used up to now.

Several statistical models were developed using combinations of classification and continuous variables susceptible to analysis by the general linear model (GLM) procedure. All two-way interactions were included in the models originally, and individual factors were gradually removed as the models were run and insignificant factors were identified. These models, which typically had hundreds of degrees of freedom and hundreds of observations, could not be run on USWCL computers, and machines at the Salt River Project were eventually used. Model reduction was an interesting exercise, as some models "behaved" nicely, reducing to forms with high r^2 values (up to 87%) and large numbers of factors, while other models seemed to "disintegrate" leaving only a handful of significant factors and low r^2 values.

In the case of SEASON vs. DAY (time of year), SITE vs. MILE (delivery location), and DAYTIME vs. HOUR (time of day) the more general classification versions of the variables resulted in "better" models. In none of the models were explicit solutions for the models' parameter estimates (their magnitudes) available due to the combination of classification and continuous variables. And the biased estimates that were provided for some of the variables were not consistent in trend or magnitude from one model to another. As measured by model significance probabilities and r^2 values, though, attempts to analyze the system with only classification variables (ANOVA) or only continuous variables (multiple regression) were not as successful. Multiple regression procedures give explicit parameter estimates, but do not allow variable interactions. The best GLM results seemed to indicate that nearly all of the proposed sources of nonuniformity were important either as main effects or as components of an interaction.

At this point, in late 1987, statistical analysis of delivery uniformity stalled. ARS staff statisticians had been consulted several times during the year and their advise followed closely, yet the results to date were minimal. The on-going work involves re-evaluating the form and content of specific variables, and using more sophisticated techniques such as principal components or factor analysis. The data is being tested for linearity, interactions, and population distributions.

Another approach for producing at least preliminary results is to make vastly simpler models and attempt to look at the contribution to nonuniformity of individual factors. Such a one-dimensional approach is probably naive given the known complexity of the GLM models, but may shed light on importance or trend of certain effects. Some of these results seem clear, regardless of how the data is subdivided: 1) larger flow rates result in more uniform deliveries; 2) shorter deliveries result in more uniform deliveries; 3) turnouts in the middle of a pool have less uniform deliveries than turnouts just upstream of a check structure.

As discussed in the CANAL MODELS report, there is apparently a working canal network model available commercially from SOGREAH in France. Acquisition of this or a similar model would allow a nonstatistical approach to identifying the sources, trends and magnitudes of flow nonuniformities. The model could presumably be tuned to mimic the operation of the WMIDD laterals, with structural and operational factors then manipulated to observe the effects. Such an approach would lead directly toward the project goal of developing new schemes for canal operations.

<u>Imperial Canal Monitoring Study</u>. Data was collected on two lateral canals of the Imperial Irrigation District (IID) between June 1986 and June 1987. These canals were roughly eight miles long, each containing about 20 to 25 farm turnouts. A number of broad-crested weirs were placed just downstream from farm canal offtakes. Measuring structures could not be placed at all farm turnouts for a variety of reasons, including: insufficient head available from district canal, lack of lined farm canals, lack of cooperation by farmers, etc. Broad-crested weirs were placed in the lateral downstream from check gates at about every two miles. It was hoped that information about in-line flows could be used to help determine delivery uniformities. To aid in this process, water levels upstream and downstream of farm turnout gates were measured in order to get an indication of relative flow changes over an irrigation. Gate openings were not monitored for either the farm turnout or the lateral check gate. A flow balance was computed for the canal reaches between adjacent in-line flow measuring weirs. The flow balance was then assumed related to the farm deliveries, and a procedure was developed for adjusting the flow balance by assigning

flow balance errors to farm deliveries. The procedure is not yet totally reliable and each estimated delivery is reviewed manually.

The flow measuring structures and the monitoring equipment were installed by IID personnel. The water levels were sensed with a float potentiometer system and the data was collected and processed with EASYLOGGER data loggers, both made by Omnidata International, Inc. The float potentiometer systems were evaluated by a several month-long test of cycling water levels. The potentiometers appear to be very stable over time, but have a slight temperature drift. Several farm flumes had been installed and monitored with strip chart recorders prior to the monitoring project start up. These sites were converted to float potentiometers in October, 1986.

Data was collected on a weekly basis for the two canals (56 monitoring stations) by ARS employee Carl Arterberry. After his transfer to Phoenix in June 1987, data collection stopped. Data from the study is currently being processed. A number of problems have been encountered in analyzing the data caused by lost data and by errors in flume zeroing. The later resulted both from errors in the zeroing procedure and from float cable slippage on the potentiometer pulley. These problems complicate the procedure for estimating delivery flows from the flow balance. Further data collection will be considered at a later time depending on the results from the current data set.

Furcation Responsiveness Study. Responsiveness is a term that describes how canal structures at furcations distribute transients or errors in flow. Depending on how a set of structures are designed and operated, flow errors may be divided proportionately or disproportionately. Responsiveness can in general be reduced to mathematical functions and better knowledge of those functions could be valuable in the training of ditchriders and in the automation of canal systems. In 1987, little progress was made on a project to study furcation responsiveness. Envisioned are computer programs to calculate responsiveness from structure settings and vice versa, and the modeling of structures in the WMIDD laterals to analyze their operation in terms of responsiveness. Significant progress on this topic of study is expected in 1988.

PERSONNEL J. D. Palmer, A. J. Clemmens, A. R. Dedrick, J. A. Replogle, J. Padilla, R. Gerard, R. Kapfer (through November 1987).

TITLE: FLOW MEASUREMENT AND CONTROL

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FLOW METERS

Flow meters can be classified into two functional groups, based either on the primary measurement of quantity of flow, or primary measurement of rate of flow. Further, all fluid meters consist of two distinct parts, a primary element in contact with the fluid that causes some kind of interaction, and a secondary element that translates the interaction into volumes, weights, or flow rates, and indicates the result for observation or recording. The secondary elements can be varied almost indefinitely, but the primary elements operate on a few simple physical principles. Thus, fluid meters can be conveniently classified according to the physical principle or the nature of the primary element involved (ASME 1972).

Basically, the fluid mass properties (volume, density, inertia), sonic properties (sound wave transmission, dispersion, reflection), electromagnetic (warping magnetic lines of force), electrical conductivity, thermal properties (conductivity, absorption), mixing properties (regular vortex formation, turbulent mixing), and optical properties can all be used to detect flow velocity, rate, mass, or volume. Many meters use mass and density properties of fluid in motion and deduce flow characteristics from momentum and energy relations. Density properties relate mass and volume. For agricultural applications, emphasis will favor meters that primarily exploit mass and density properties of fluids in motion because of their usually rugged nature.

Most flow measuring devices do not in themselves control the flow but are usually used with a slide gate or a valve that regulates the flow to a desired flow rate as read on the meter. This is of particular concern for irrigation applications where flows are more likely to be regulated than simply monitored. These meters may be totalizing meters or rate meters, depending on the attached instrumentation.

For the usual small field ditches with concrete linings, pre-computed ratings have been prepared and published by Clemmens and Replogle (1980), and by Bos et al. (1984). The usual configuration is a trapezoidal, broad-crested weir, with an approach flow ramp.

Dimensionless ratings for average roughnesses and profile lengths were presented for partly full circular culverts fitted with similar sills (Clemmens et al. 1984). These ratings can be converted into calibrations for portable flumes built from short pieces of plastic irrigation pipe, larger than 100 mm in diameter. However, direct computation by the computer model (Clemmens et al. 1987) for the specific construction materials and lengths provides a slightly more accurate equation for the specific configurations that can also be used for portable flow measuring.

Discharge equations suitable for portable flumes constructed from common plastic pipe sizes, as indicated in Fig. 2, are provided. The dimensions are shown in terms of nominal English-unit inside pipe diameter, and the strict metric conversion to that nominal size. Direct equations for 4-, 6-, 8-, 10-, and 12-inch sizes are given in terms of a modified power function, Fig. 2. which will satisfactorily reproduce the computer-model generated tables to within about 1%. This width is the most important measurement in the flume, except for the head measurement (Bos et al. 1984). For the head measurement, the use of a translocated stilling well is recommended. This method transfers the upstream depth reading to an easily measured location above the sill at the flume outlet. The reason for this translocated stilling well is to conveniently reference the upstream head to the sill floor without the necessity of accurately leveling the flume, thus making it more practically portable (Bos et al. 1984). The alternate (upstream) gage reading location should be used only if the flume can be conveniently, or permanently, leveled.

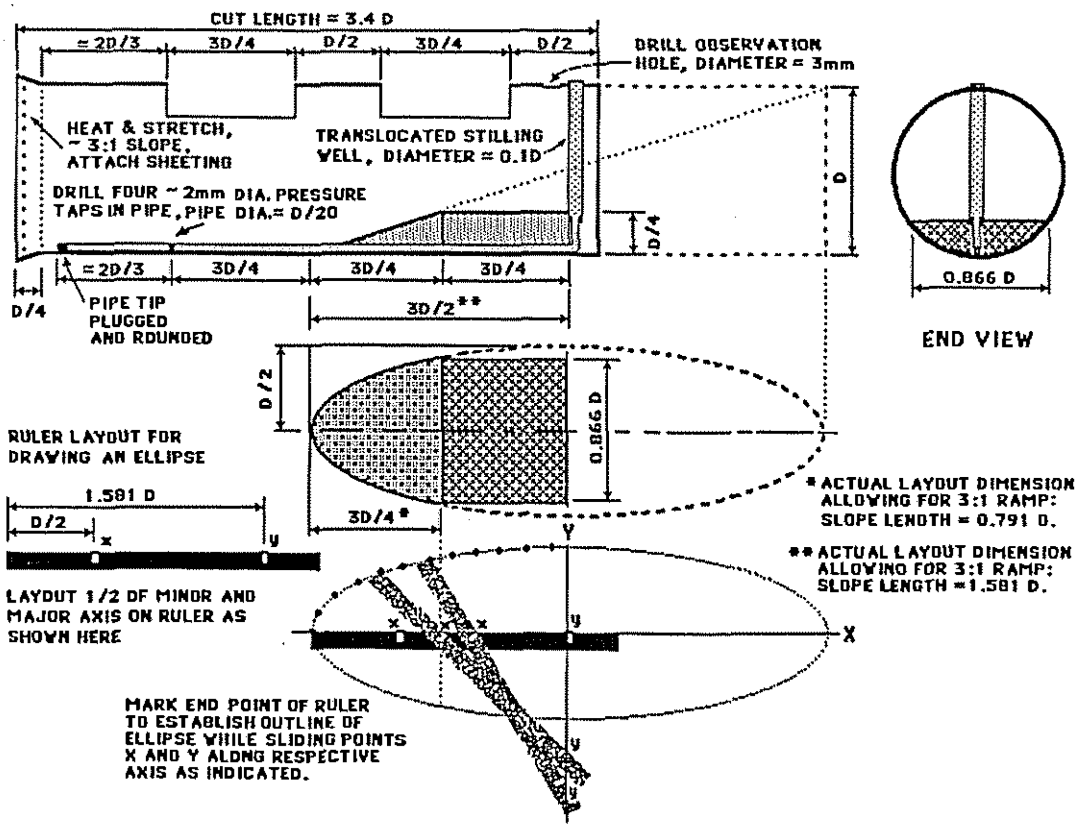


Figure 1. General layout and dimensions for circular portable flumes (method for layout of elliptical ramp section is shown) constructed from standard plastic pipe sizes (See Table 1).

Table 1. DIMENSIONS FOR PIPE-SECTION FLUME

	101.6mm (4-inch)	152.4mm (6-inch)	202.2mm (8-inch)	254.0mm (10-inch)	304.8mm (12-inch)	381.0mm (15-inch)
D1	101.6mm	152.4mm	203.2mm	254.0mm	304.8mm	381.0mm
DC	101.6mm	152.4mm	203.2mm	254.0mm	304.8mm	381.0mm
PC	25.4mm	38.1mm	50.8mm	63.4mm	76.2mm	95.3mm
BC	88.1mm	132.1mm	179.9mm	220.1mm	264.2mm	330.2mm
AL	76.2mm	114.3mm	152.4mm	190.5mm	228.6mm	285.8mm
BL	76.2mm	114.3mm	152.4mm	190.5mm	228.6mm	285.8mm
TL	76.2mm	114.3mm	152.4mm	190.5mm	228.6mm	285.8mm
Amm	0.002999	0.004126	0.005068	0.006142	0.00718	0.00860
Bmm	0.14	0.42	0.84	1.05	1.26	1.60
U	1.684	1.687	1.693	1.691	1.689	1.690

$$\text{EQUATION:} \quad Q_{1/s} = A_{mm}(H_{mm}+B_{mm})^{U}$$

$$0.05\ T_1 < H_{mm} < 0.7\ T_1$$

Froude Number Scaling: Froude Number Scaling can be used to "adjust" a calibration equation to any other size (Bos et al. 1984). For example, the 304.8 mm (12-in) equation can be used to predict the 152.4 mm (6-in) pipe calibration within reasonable limits. Linearly scale all head values in half (scale ratio, R = 0.5). Thus, a 100 mm head reading in the larger flume will correspond to a 50 mm head reading in the smaller flume. By hydraulic similitude laws, the discharge at the half scale is reduced by the scale ratio (0.5) to the power of 2.5, or will be 0.1767 times the 304.8 mm (12-in) values. The equations furnished shows Q(304.8mm) for h=100 mm to be 17.51 l/s. Taking 0.1767 times this would indicate a flow for a 152.4 mm (6-in) flume at 50 mm head to be 3.096 liters/sec. Compare this to the directly determined value for the smaller flume at an entry of half the head value, or 50-mm, and obtain 3.075, a difference of about 0.7%. This difference results primarily because the same material roughness is used for all sizes, that is, the pipe roughness is not expected to scale down.

Similarly, suppose the 304.8 mm (12-in) pipe were really 298 mm (11.75 in) in diameter, then the flow head values need to be reduced by the small ratio, 298/305, and the discharges reduced at these new head values by (299/305) taken to the 2.5 power (0.944). This assumes that the sill width was is scaled from 0.866 D. However, if the user chooses to force the full unscaled sill width into this slightly undersized pipe, slightly distorting its circular shape, then the given rating will be suitable whenever the distortion causes less than 1% change in the width of the throat flow area at any depth.

The more precise adjustment equation can be developed from the table values for the nearest size, and is:

$$Q_a(1/s) = R^{2.5}\ A_{mm}(H_{mm}/R + B_{mm})^{U} \tag{1}$$

Where Q_a is the adjusted discharge for the adjusted diameter, D_a, and R is the scaling ratio, D_a/D_c. All lengths of construction should be scaled by the ratio R. However, for small changes of less 10% in any measurement except the throat width, the construction scaling can be ignored.

Such a flume in circular section was designed and constructed for cooperators in Pakistan for portable field use. They report satisfactory construction methods and use.

Ultrasonic Meter for Irrigation and Drainage Flows

An particular exception to high cost and lack of ruggedness usually associated with ultrasonic flow meters may be a recently introduced device designed for measuring both flow rate and total flow in concrete pipelines flowing full. The particular units observed were sold to the New Magma Irrigation District and to the Central Arizona Irrigation and Drainage District, both in Arizona, by Badger Meter, Inc., Industrial Products Division, Tulsa, Oklahoma, and were developed under U.S. Bureau of Reclamation, Central Arizona Project, Contract No. 6-CP-30-04560. (Mention of Brand Names does not constitute endorsement by the author or the US Government.) They were put into operation during the fall of 1986.

Called the "Model 4420 Compu-sonic" meter, it is a transit-time, single path, ultrasonic flowmeter. It uses battery power, with solar panel recharging, and is microprocessor controlled to allow a sleep/wake-up mode to conserve power. There are two LCD displays, one three-digit display for flow rate and another of six digits for totalized flow volume. This is programable in BASIC to particular units. A serial communications port allows accumulated flow data to be dumped to a data logger. The meter has two internal totalizers. One is non-resettable and is displayed continuously. The other totalizer can be temporarily displayed in its place and can be reset to zero.

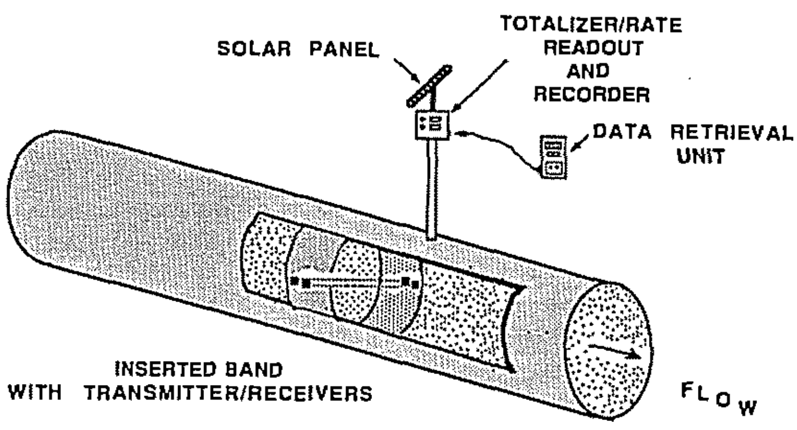


Figure 2: Single Path Ultrasonic Flowmeter of the Type Used in Irrigation Applications

The sonic sensors are installed about 30 meters downstream from circular slide gates in pipes that are about 0.75 meters in diameter. The pipelines are usually slightly curved. The underwater sonic sensors are pre-mounted on a stainless steel circular band that was inserted into the pipe outlet end and expanded with a special spreader bracket to a tight fit. The pipe outlets into a box below the grade of the farm canal it supplies so that the pipeline stands full of water between deliveries. This may inhibit growth of crystals on the sensor faces. The sensors sample a single horizontal path across the pipe for 16 seconds every 15 minutes, or when manually activated, at the rate of 156 sub-samples per second. The sensor wires exit through a hole into a plastic pipe sealed to the top of the larger pipe being measured. Best accuracy is claimed for flow velocities in excess of 0.5 ft per second, but detection of flow is practical at velocities as small as 0.1 ft per second. The angle of the single path beam is at 22-degrees across the pipe.

Field checks were conducted on a sample of six of the devices in April and June, 1987, using a portable broad-crested weir in field channels downstream from the meters. Four ultrasonic meters supplied canals that could conveniently accommodate portable long-throated flumes. The two other canals could not be readily measured.

The observed flow rates at the 6 sites ranged from 81 to 297 l/s. The standard deviations of the sampling groups ranged from ±4.5% to ±14.8%. Of the four sonic meters that were flow checked, the average indicated flow rates (and their Standard Deviations) were 81±8.7%, 146 ±4.5%, 232 ±6.6%, and 299±8.2% l/s. These compared to flume measurements of 80.1, 148.7, 227, and 306 l/s, respectively (+1.11%, -1.85%, +2.16%, -2.34%). The variability in the individual readings indicate that water jets from the partly open gates may be reaching the meters in a swirling random pattern, probably due to the pipe curvature. The pipe entrance gates are round and were about 3/8 open.

Manually sampling at one 16-seconds sample per minute and as rapidly as practical, showed little significant difference as long as 10 or more samples were obtained. This would indicate that the assumed swirling jet was sufficiently random so that about a 3-minute sampling period could indicate a good average flow-rate. Thus, the long-term totalizing functions of the meter are expected to be well within acceptable standards. However, the meter is inconvenient to use for setting gates because of the necessity of having to compute averages. A manually selectable, single-sampling period of up to 3 minutes, instead of 16 seconds, would appear useful in overcoming the hydraulic limitations of these particular styles of gated-pipe outlets.

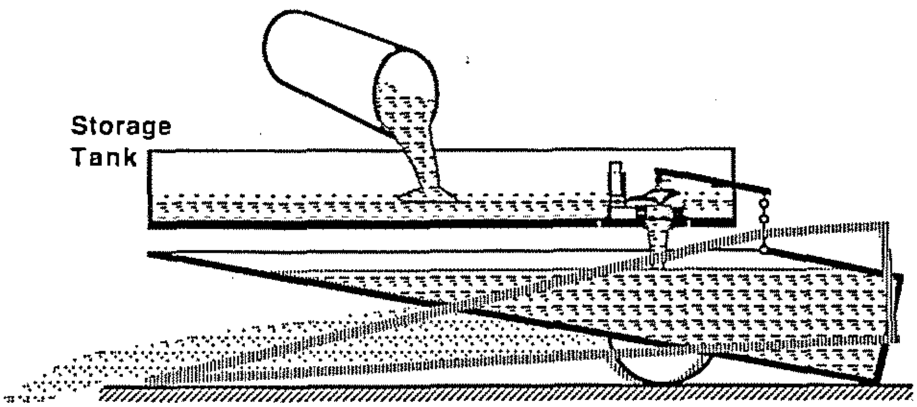
Table 2. Field Test Results Comparing readings for Sonic Meters in the New Magma Irrigation District, NMID (Arizona) and the Central Arizona Irrigation and Drainage District, CAIDD, with those from a portable Flume (Data is in field units as-read: 1 cfs =28.32 l/s)

	Meter NMID-15 Reading	Meter NMID-4 Reading	Meter NMID-13 Reading	Meter NMID-13 Reading	Meter CAIDD-1 Reading	Meter CAIDD-2 Reading
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
	7.9[a]	11.2[a]	8.0[a]	9.4[b]	2.9[a]	5.4[a]
	8.3	10.7	6.5	8.3	2.9	5.2
	8.2	10.0	8.0	8.5	3.1	5.1
	9.0	11.0	7.9	8.8	2.7	5.5
	8.2	11.1	9.7	7.6	2.8	5.3
	7.9	11.2	9.5	6.3	2.6	5.3
	8.6	10.6	9.1	9.5	3.3	5.0
	8.6	10.5	5.8	5.9	2.9	5.0
	7.0	10.5	9.7	9.0	2.9	5.0
	8.1	9.3	6.6	8.9	3.0	5.0
	9.2	9.6	9.5		3.3	5.3
	12.5	7.5	8.5		2.7	5.6
	9.5	8.6	7.4		2.5[b]	5.1[b]
	10.2	9.3	8.8		3.1	5.3
	9.9	8.5	9.3		2.7	5.2
		9.3	7.8		2.5	5.2
			8.0		2.9	4.6
			7.8		2.9	4.9
			6.6		3.3	5.4
			8.4		2.9	5.0
			8.4		2.5	5.1
			9.3		2.5	4.9
			9.0		3.1	5.2
			8.0		2.7	5.2
			8.1			4.7
						5.4
						5.4
AVE.(cfs)	8.18	10.55	8.35	8.28	2.86	5.16
S.D.(cfs)	±0.54	±0.86	±1.24	±0.97	±0.25	±0.23
CV	0.066	0.082	0.15	0.12	0.088	0.45
Flume(cfs)	8.03	10.8	c	c	2.85	5.25

[a] Manually started sample every minute (16 seconds out of minute).
[b] 16-second sampling restarted as rapidly as button could be pressed after previous 16-second sample.
[c] Flume flow measurement not made because of poor canal access.

ON THE DESIGN OF WIDE RANGING METERS FOR SMALL DRAINAGE FLOW EXPERIMENTS

The question was posed to us concerning the need in drainage research for an accurate reliable meter to measure drainage flows over an extremely wide range, from drip flows to about several liters per second. Pump systems were discarded because of possible power problems. The design should also be constructable from common components because of the low number to be built that would not support a complex manufacturing process. A candidate design is a style of tipping bucket made from plastic pipe sections. It would differ from the usual tipping-bucket system in that a holding reservoir also made from a short pipe section, would be mounted above it with a flush valve activated to close at the start of each tip such that the storage reservoir would captured the flow to add to the next tip. This would appear to be a viable method to reduce or eliminate the sensitivity of these devices to flow rate. It would be expected to halt the pass-through flow during the tipping process which would vary with discharge rate. By halting this flow, the major source of meter error will be controlled. Also, it would consist of only one tipping section, which is unlike the two-compartment standard versions. This would appear to allow easy adjustment of the tipping volume by use of auxiliary sliding weights to adjust the over-balance position.



TIPPING-BUCKET FLOWMETER
SINGLE-BUCKET STYLE

FEATURES:
1. Storage of flow between tips
2. Rapid shut-off valve
3. Bi-stable support for rapid tip

Figure 3. Tipping bucket flow meter concepts.

THE BAG-TYPE FLOW CONTROLLER

The DACL (dual-acting controlled-leak) float valve system was simplified into a vertical mounting and attached to the inside of a 3-ft section of 15-inch plastic pipe that served as a stilling well. This pipe and valve mounting was then attached to a 12-inch wide vertical slide gate made for canal outlets by Fullerform company. The mechanism was chosen because it provided a ready made method for raising and lowering the float-valve and stilling-well assembly. The entire slidegate, stilling well, and valve assembly was placed on a skid mounting so that it could be moved from channel to channel.

A bag with hose fitting attached was made from heavy duty reinforced plastic material by Phoenix tent and Awning company. The bag was made from a piece of material 4-ft square. The finished bag was about 22 inches by 43 inches. The edges were sewn and heat sealed. The hose fitting was glued into place with material called sho-goo that is used to repair tennis shoe soles. It eventually hydrated and pulled off. A mechanical clamp system was then devised to use sections of 12-inch lay-flat tubing.

Meanwhile, the tests on the bag placed under a sharp edge of an irrigation jackgate, 46-inches wide, was conducted. The bag was restrained with ties so that about 25% of its width was under the gate. The rest was upstream. The bag filled with water at the pressure of the outlet side of the gate. Thus, whenever a leak on the fittings exposed to the upstream pressured occurred the bag inflated and attempted to obstruct the opening. In this setup of controlling the upstream depth in the channel, the control valves were under water. Any leakage there would tend to fill the bag and slightly increase the drainage flow-through. This would not affect the basic operations of the device. The pressure differences on the two sides of the outlet had the effect of bulging the one-quarter of the bag through the gate and forming a cylindrical bead, in this case about 8-inches in diameter, that shut off the water by pinching back on the downstream side of the gate. The upstream part was basically deflated except for the result of tensions in the bag itself.

Because of the sharp edge, small amounts of filling water was able to cause rather rapid changes in flow on a cycle time varying from about 3 to 6 minutes. The volume of the level-top channel (60 feet by 4 feet) was such that the bag changes were faster than the channel response so that cycling occurred. the cycles had an amplitude, tip-to-tip, of about one inch in some cases and about one-half inch in others that was related to the stage of flow and the quantity of by-passed flow. That is, the amount of water required to flow into or out of the bag to cause a particular change in controlled outflow regulated this over-shoot cycling. It also changed the frequency of the cycling. By placing a pipe tee in the line and adding a surge tank, in the form of a 50-gallon drum, in parallel to the bag flow, the volume of water needed to actuate the bag was significantly increased because now the surface area and depth equal to the pressure change being transmitted to the bag must also be satisfied. This procedure offered a way to control the amplitude on the cycling, but also lengthened the basic response frequency from about 6-minutes to about 12-minutes. Again this appears to be a function of gate discharge that is being bypassed. With the 50-gallon drum volume in the system, the system would overshoot on one cycle then completely damp to the basic control band of the DACL valves, which was on the order of one-eighth inch, within two cycles. Once stable, the surge drum could be removed from the system and oscillations would not restart until an outside disturbance was introduced.

Air in the coiled flexible hoses was a problem. This air in the lines caused several instances of bad data and emphasized the importance of proper line bleeding which must be dealt with in field installations. This can probably be done by replacing all flexible hoses with hard pipe plumbing and venting all high spots. The vent pipes would need to rise above the expected pressure gradient. This would have a maximum value that could approach the pressure of the water source used for control purposes. All pipes would need to be sloped upward to these vent points.

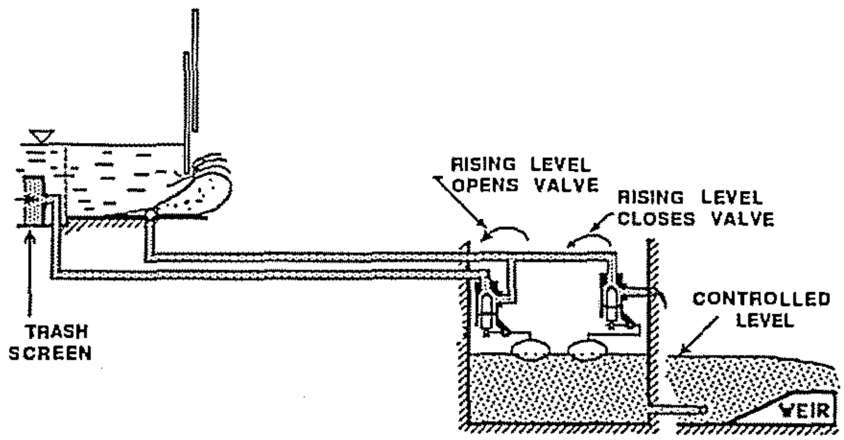


Figure 4. General configuration of a bag-DACL controller used under a vertical slide gate.

The bag was then affixed into a 15-inch plastic pipe section about 6.5 feet long and used to control the level of flow as before. This combination requires much more fluid to be transported into the bag to cause control changes and stability was more easily gained.

However, continued testing with this system showed some peculiar instabilities that were not anticipated. The cause may be a function of the way the bag was made. Lay-flat tubing is available in 12-inch size. To fill a 15-inch pipe, a ten foot section was folded to form a double bag. The fold was fitted with a piece of wire mesh inside in an attempt to maintain an open pathway from one chamber to the other. The fold was looped over a constraint to hold the folded bag upstream inside the pipe outlet. The orientation of the two lay-flat tubing layers was horizontal--one on top of the other. The actuating flow entered the top layer of the two-part bag. This top layer volume had to be satisfied within the confines of the pipe exterior water pressure and the tensions in the tubing wall. Only then would flow tend to migrate around the upstream constraining fold into the bottom layer. The behavior of the system would suggest in retrospect that the wire mesh was not extensive enough. While flow could seep around the bend, there may have been a pinching-off of flow just beyond the ends of the folded piece of wire mesh. This may have tended to trap flow in the bottom bag fold and prevented its free movement to the inlet/outlet piping. When movement did occur, it may have caused the observed instability and pronounced overshoot.

ON THE DESIGN OF CONSTANT-HEAD FACILITIES

Most hydraulic laboratories use a constant head tank facility of some sort. These facilities depend on pumping to an elevated tank whose surface level is held within narrow bounds by the ability to spill excess flow over a long weir. The weir is usually a grouping of boxes, or chimneys, that rise out of a cap fitted over the tank. The chimneys provide an aggregate weir length based on their perimeter that may total as much as 100 feet in spill length. Providing such a tank to control pumping surges is usually costly, especially when providing by-pass plumbing and other features.

We have designed a "no-spill" version that we feel should be tested. It is based on the constant discharge devices described above. The general features are shown in Figure 3.

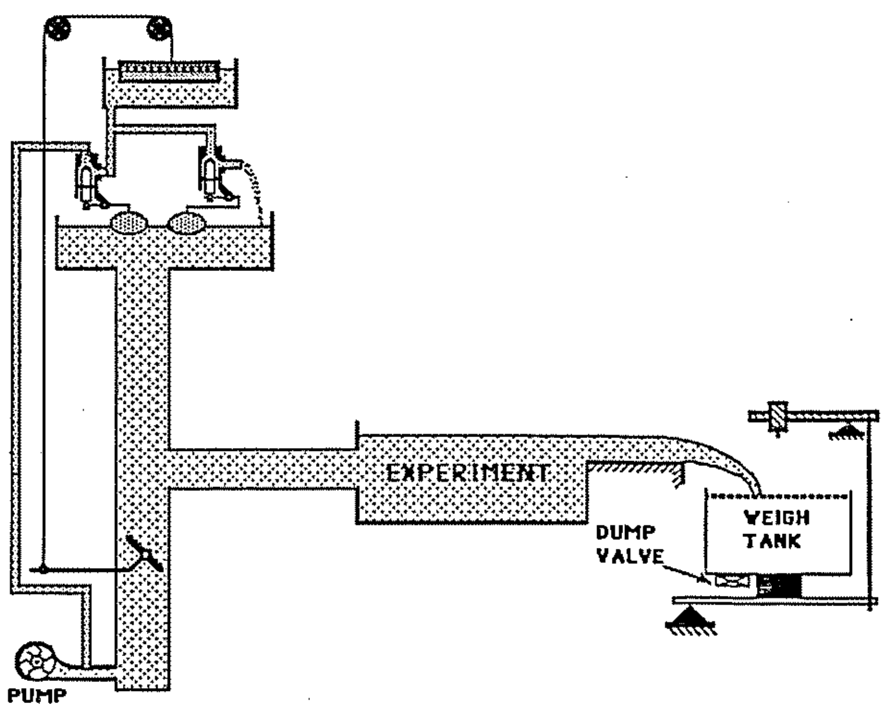


Figure 5. Constant head facility.

SAMPLING DRAINAGE FLOWS

Recent splitter-sampling design concepts were presented at the Winter Meeting of the American Society of Agricultural Engineers. These concepts appear to be able to accurately sample total sediment load and also appear accurate enough to provide flow rate and volume information, when sufficient elevation differences are available in the channel at the sampling site. Full details are published in the conference proceedings. In brief, the following design theory and construction recommendations result from the study and report.

Sampling runoff water that is carrying a heavy sediment load has usually posed at least two major problems: (a) accurate representative sampling of all sediment sizes, and (b) maintaining a uniform ratio between the sampling rate and the flow rate for all discharges. Most systems have used a flume or weir for reasonably accurate total flow rates and have then attempted separate sediment sampling with variable, but usually high sampling errors.

Coshocton wheel samplers and H-Flume combinations represent one system that has been used extensively in studies of soil erosion from small drainage areas. They have performed reasonably well under field conditions when properly installed and maintained. These devices have capacities that have usually limited their use to drainage areas of less than one acre.

In an effort to remove these size limitations, a hypothetical sediment sampling system is presented for sampling both bedload and suspended particles that should be highly accurate, depending only on adequate construction tolerances. No construction drawings are offered. Rather, a conceptual sketch to prompt designers toward correct engineering methods are provided. These describe the "ideal" total-load sampler and briefly compare how well historical samplers approximate ideal sampler behavior.

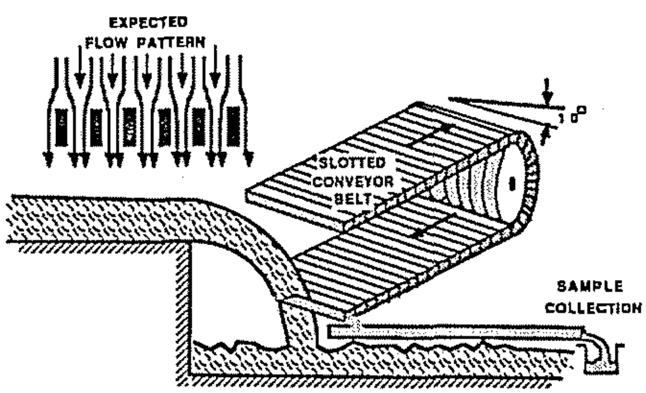


Figure 6. Schematic of a conceptual ideal sampling system for suspended and bedload sediments, showing sampling slot and the guard slots that would apply to moving or stationary sampling racks.

Theoretical Considerations

The concepts for an idealized bedload and suspended load sampler are simple. Imagine that the entire flow can somehow be dumped onto a moving conveyor belt as shown schematically in Fig. 1. If the belt is divided into slots of equal width, each slot necessarily must collect an equal share of the flow rate, if the belt moves at constant velocity. The slot width is effectively the distance from the center of one partition to the center of the next. The partitions between slots do not even need to be thin because any flow striking their edges must eventually fall down a slot. The slot edges may be round or square, or some other configuration, as long as all slots are alike. The friction of entry into the slot and back pressures from the non-sharp partitions are all compensated as the flow spreads to use a wider portion of the conveyor belt. The cross-sectional shape and the angle of attack of the falling jet of water on the sampling belt are of no consequence, again because all of the flow must fall through the slots. Thus the 10-degree tilt in the direction of the general channel slope, as shown in Fig. 1, is a practical way of handling tree limbs, oversized stones, and other trash.

The speed of the belt can have little effect unless it is so fast that it splashes the water and sediment beyond the boundaries of the belt, or is so slow that it fails to cycle sufficiently during a flow event. Water splashed or accelerated from one slot will go down another some distance away. The faster the belt speed, the greater this distance. This has practical implications for our final design recommendations. Slot width affects the maximum particle size in the sample collected. Larger rocks, sticks, and stalks would exit the down-slope side of the belt.

Imagine that each slot discharges to a separate tank. We would find at the end of the flow event, that the entire runoff was stored in the tanks and that each tank contained the same volume accurately representing a share of the runoff event equal to the share of the belt circumference that the slot represents. Total runoff water and total sediment transported could therefore be determined from any one tank and the remaining tanks could be discarded. Thus, only one slot needs to be mounted on a skeleton belt, or alternately on a traversing rail-mounted device with microprocessor timing and velocity control to simulate both belt length and travel speed.

As an example, a 10-mm slot on a 10-meter belt would collect 0.1% of the total discharge. For time-discharge-rate determination, a sample bottle would need to be collected from the slot on each revolution, or as often as needed to adequately define the curve. The volume caught would be directly related to flow rate, using knowledge of time between samples. The necessary size for each bottle would depend on the slot width and slot speed.

Usually, the sample size is too large. We can accurately reduce the sample size in several ways by manipulating our ideal sampler. The slot width can be decreased, but this will limit the particle size that can be sampled. The length of the belt can be increased. This reduces the ratio of slot width to total belt length and proportionately reduces the sample size. The sampling rate could be microprocessor controlled with discharge rate, or other criteria, by simply simulating a changed belt length (by changing traversing period and velocity).

Without changing the belt length or the slot width, a mechanical diverter valve and counter can reduce the sample size by keeping only one sample out of five or ten belt revolutions. If the individual sample pulses are too large for the sample bottles then the belt speed can be increased.

With only one slot on a skeleton belt and no neighboring slots, the slot wall thickness becomes important since there are no confining pressures from the other slots. Also, high belt speed can cause splashing-out of sample with no compensating splashing-in of sample. High belt speed reduces the effective slot "window" seen by the particle and large particles that should have been sampled are bounced from the moving edge, again with no compensating bounce from neighboring slots. These neighboring, or guard, slots should approximate the entry shape of the real slot (see Fig. 1). It should be noted that the top edges of the slots and even the slot wall slope need only to be alike, as illustrated in Fig. 1. This allows slot construction from readily available structural shapes. Some shapes, such as the structural angles, offer good stiffness in the lateral direction, reducing spacer requirements. In fact, water may tend to run too far down slope on wide flat-topped bars, increasing the belt width requirements.

We can reason that thicker slot walls cause higher back pressures and would require more guard slots. Likewise high speed traversing would cause more splashing and would again require more slots. Thus, for edge thicknesses on the order of 10 to 20% of the slot opening, a minimum of two guard slots should probably be provided on each side of the real slot. For knife-edged slots, this might be reduced to one guard slot on each side. High speed traversing on the order of 25 to 50 cm per second can probably be handled by two guard slots on each side. These slot recommendations have not been verified by laboratory testing.

Design Recommendations

Recommendations for the design of a practical total load sediment sampler are as follows:

1. Select a site that can provide up to one-meter of overfall if possible. One-half meter overfalls can be made to work but at greater expense. Lesser heights may require pumping.

2. Fit a traversing mechanism with a slotted sampler with at least two guard slots on each side constructed and mounted with a 10-degree downstream slope to help clear debris.

3. Make the slot at least as wide as the maximum sample particle size to be collected. Wall thickness of the slot should be 1 to 3 mm or less. Extreme sharpening may actually retard self-cleaning.

4. Provide 60-cycle A.C. electric power and an oversized AC-motor to assure uniform speed of the traverser and chain-drive mechanism which should allow continuous cycling of the chain. Exact regulation of the

motor speed to a fixed value is not required because the sample percentage is the ratio of slot width to chain length. In the usual case of back-and-forth traversing the effective chain length is halved.

5. A cycle counter and diverter valve are is suggested as a practical way to control sample size. For example, every tenth traverse can be saved.

6. If timed samples are collected, then each sample pulse can be changed in volume by the chain drive speed. This will not change the total sample volume collected -- only the slot width, chain length and diverter valves can do that.

7. If the sampler can be constructed as described and time delivery of the sample can be recorded, then direct sampling from a channel overfall without a flume contraction is recommended. Flumes usually disrupt the movement of sediment by delaying it with respect to the original stream flow. Outfall shape of the flow is unimportant.

8. Reasonably satisfactory stationary samplers can be constructed to work well if a sufficient number of sampling slots, with guard slots, are provided across the nappe to reproduce the behavior of the true event to sufficient accuracy, usually 3 to 9 samplers in the entire rack. A single slot, with guard slots, can be expected to work well only with rectangular overfalls where the sediment distribution is well distributed across the floor of the rectangular outfall, and the lateral differences in velocity patterns are small.

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TITLE: MATHEMATICAL MODELS OF CANAL SYSTEM HYDRAULICS

SPC: 1.3.03.1.d CRIS WORK UNIT: 5344-13000-001

INTRODUCTION

This report provides a brief overview of the existence, capabilities and limitations of mathematical models for the determination of flow and water levels within irrigation canal systems. These models can potentially be used to provide assistance in improving the operation of existing and proposed irrigation canal distribution networks. This discussion does not include information on methods for the control of canal networks, but discusses the ability of models to model control algorithms along with channel hydraulics.

CURRENT MODELS

Recently Developed Models: Because of the scope and complexity of these models, there are only a few such models available which are of enough sophistication for general use. Some of these models have been presented in the literature, but other have not been. The models of canal networks investigated include the following:

- The USU Main System Hydraulic Model developed by Francis Gichuki and the USU Canal Hydraulic Model developed by Gary Merkley (Dissertations, Utah State University, Logan, UT, 1987.) Each author developed his own software package; however, the fundamental algorithms which drive the two models are essentially the same.

- The Irrigation Conveyance System Simulation Model developed by David Manz (Dissertation, University of Alberta, Edmonton, AL, 1985.)

- The Microcomputer Simulation of Canal Operation Model developed by Douglas Hamilton and Johannes DeVries (Thesis, University of California, Davis, CA, 1985.)

- The Unsteady Model (USM) developed by the U. S. Bureau of Reclamation (Denver, CO, late 1970's.)

- The HYDRA Network Model developed in France, and marketed in the U. S. by Flow Science, Inc. (Pasadena, CA.)

- The CARIMA Network Model developed in France by SOGREAH, and marketed in the U. S. by Forrest Holly, University of Iowa, Institute of Hydraulic Research (Iowa City, IA.)

Restrictions: Various restrictions within the above models limit their usefulness for this project (Wellton and Imperial monitoring projects and the general study of canal networks). The major restrictions are discussed below.

The method of characteristics is the fundamental solution technique for the Bureau's USM program. The method of characteristics can be computationally inefficient, and it can generate serious problems with certain boundary conditions. It has been superceded in recent years with finite difference methods which are considered to be generally superior for this application.

With the exception of the HYDRA Network Model and the CARIMA Network Model, the remaining models are restricted to (purely) nonbranching networks, or branching networks wherein the branch nodes include only one submerged structure. The reason for the above restriction is that a series of in-line reaches may be handled efficiently and easily from a computational point of view. For example, recursive (double-sweep) algorithms trace the series of reaches (e.g. from source node to distal node and back) for each time step. Each node is treated as a special case of the computational grid points created within each reach, hence the solution algorithm is nearly identical to an algorithm designed for a single reach. For these reasons, these models also require free flow at the turn-out structures.

The HYDRA Network Model from Flow Science and the CARIMA Network Model from SOGREAH come closest to providing the full capability sought for general canal network modeling. Although it appears that Flow Science is in this instance primarily a vendor (the code is supplied by an engineering firm in France) much of the code was reportedly written by their senior engineer, Dr. Greg Gartrell, when he was employed by this firm several years ago. Flow Science claims in-house capabilities for any necessary program customization.

Dr. Forrest Holly of the Iowa Institute of Hydraulic Research worked for SOGREAH and reportedly wrote much of the code which now comprises the CARIMA package. He currently represents the interests of SOGREAH in the Unites States. Although the actual sale of the software would be handled by the parent company, it appears that any training could be done in Iowa City, under the supervision of Dr. Holly.

Model Considerations: The main considerations in the selection and use of canal hydraulic models are:

1. The governing equations used to model the hydraulics (e.g. full hydrodynamic, zero inertia, etc.)

2. Whether the hydraulic equations are non-dimensionalized, and to what extent they are linearized.

3. Whether or not certain ill-behaved boundary conditions are identified and properly handled by the model (e.g., hydraulic jumps).

4. Whether smoothing techniques can be applied in situations where rough profiles are generated from computational side effects.

5. Whether the model can handle difficult modeling situations, such as supercritical flow, or the momentum contribution of outflows (which can be a significant portion of the flow in small canals.)

6. Specifically, can the model accommodate hydraulic jumps that move with respect to space and time (of interest, but not crucial).

7. Whether the model can handle the small lined canals and laterals typical of irrigation distribution systems, as opposed to river channels.

8. Whether transitions to and from gate submergence are handled with appropriate sensitivity.

9. Whether control structure density is limited due to model development in a riverain/eustuarain environment.

10. Whether the model can handle rapidly varied flow over short periods, such as the case when gate openings are suddenly changed in sequence down a lateral by the ditch rider.

11. Whether the network solution technique allows submergence at any or all nodes within the network, and whether it allows looping.

12. Whether different control structures may be suitably modeled, or added to the model.

13. Whether common control structures are currently available, such as culverts, inverted siphons, and others which are typical of small distribution systems.

14. Whether a methodical, conceptual approach to control structure type and function could be implemented.

15. Whether a feedback mechanism can be implemented whereby water levels can be used to control gate movements.

16. What operating system, programming language, and compiler specifics were used.

17. Whether the model will fit on an IBM PC-AT, an AT with an enhancement card, or a micro-VAX.

18. Finally, the model cost, the site license options, provision for modifications to the existing code, and privileges regarding the copying and distribution of certain embedded algorithms (such as gate control algorithms) for academic purposes.

UNSTEADY FLOW MODELING

The primary issue with respect to unsteady flow modeling was whether or not implementation of the full hydrodynamic equations would be necessary. If not, it would be necessary to know which of the "subsets" of these equations should be used. For the sake of brevity, this report does not include a review of the various approaches mentioned in the literature. The practical outcome, very simply, was the full hydrodynamic equations must be used to attain the level of utility envisioned for this project. Almost all of the models reviewed were based on these equations. Furthermore, it would be reasonably convenient to implement these equations in a new model. The Priessmann scheme, which is used to solve the finite difference schemes, makes such an implementation very straightforward. (See also the next section, NETWORK MODELING, for a more comprehensive description of the Priessmann scheme.)

It would be desirable if non-dimensionalized forms of all hydraulic modeling equations were used. This would allow development of different or improved applications from the existing code with little restriction.

Another very general consideration was the proper modeling of boundary conditions, and consequent instability problems if boundary conditions were modeled improperly, or if they could not be modeled as precisely as one might desire. This aspect of the problem of modeling remains to be investigated, in that the schemes outlined so far give as much mathematical utility as can be attained with a one-dimensional flow model. Although some boundary condition environments have been thoroughly investigated, it appears that others must be researched as models are developed and tested. It must be noted here that some instability problems are (presumably) unavoidable, and are typically "solved" using smoothing routines that filter out local disturbances without influencing the integrity of the solution.

Finally, not all aspects of unsteady flow modeling have been sufficiently researched, or at least incorporated within the currently available research models. To wit, outflows over side weirs result in energy losses that heretofore have been ignored, or modeled in less than satisfactory ways. There are other similar issues that provide for substantial research interest (and potential modeling uncertainties.)

NETWORK MODELING

Much of the investigation foundational to this report was focused on the problem of network modeling. Current approaches usually allow for a restricted form of branched network modeling.

Network Modeling, with Restrictions - The standard procedure used by current models has been called the Preissmann double-sweep algorithm. One can think of this approach as consisting of two elements.

The primary element is the Preissmann scheme for handling the finite difference solution to the full hydrodynamic equations, as applied to a river or canal reach. This consists of writing the St. Vennant equations so as to define (typically) a flow and a depth value at each computational grid point along the reach. The grid points are imaginary. They have nothing to do with the physical environment, except to start and end with the starting and ending points of the reach in question. For any given reach, this results in a sparse matrix with five bands--two above the main diagonal, and two below. The unknown vector consists of a.) flow and depth pairs for each interior grid point, and b.) an additional pair of unknowns for each node point. The node unknowns consist of the flow, the depth, or some other variable in lieu of the depth depending on the boundary conditions.

The second element is the recursive algorithm used to solve the resulting sparse matrix. It is known as the double-sweep method. Recursive algorithms are very efficient in terms of memory requirements and execution time. The number of operations required to generate a solution using a standard Gaussian elimination routine is proportional to N cubed (where N is the order of the matrix, and where only multiplicative operations are counted). For a double-sweep routine the number of operations required is proportional to N. The double-sweep method is based on separating a matrix into its upper and lower triangular matrices, and then (with some dexterity) implementing a gaussian solution. The Thomas algorithm provides a simple comparison--it is used for matrices with only three diagonals. Deriving the Thomas algorithm takes less than five minutes, and illustrates in an uncomplicated way the concepts involved.

When in-line (nonbranching) networks are modeled, the above approach can be used with virtually no modification of any significance. The flow conditions at the hydraulic structures (nodes) are handled within the matrix in a manner similar to the computational grid points, so that the structure of the matrix remains unchanged. In other words, the Preissmann scheme is modified slightly, but the double-sweep method applies as before.

When branching networks are modeled, the above approach works if critical flow is guaranteed at all but one branch within each node. With this restriction, the network really consists of one or more nonbranching networks which--though connected in terms of flow--are hydrodynamically isolated by virtue of critical flow at the connecting structures.

Unrestricted Branching Networks - Mathematically, the environment changes significantly when one attempts to model branching networks wherein submergence can occur anywhere throughout the network. Also, the possibility of channel looping remains unaccounted for using the above double-sweep algorithm.

For branching networks, whether consisting of tributaries, distributaries, or both, a technique exists whereby a solution can be obtained with little extra computational effort. If the network topography is analyzed properly, the double-sweep algorithm can be systematically applied to each reach (in a pre-defined order), with intermediate calculations performed at each node, so as to tie the system together. The result is that the calculations start at the source node(s), they proceed in an orderly manner to the distal node(s), and then return again to the source. This insures that downstream conditions are accounted for in upstream pools, regardless of the type and number of branches.

Another extension to the double-sweep algorithm is available for looped networks, whereby a matrix of node coefficients must be solved for in addition to the ordered sweep through the computational grid points. In this case, each node is not simply affected by its adjacent pools, but also by conditions within non-adjacent nodes and pools. Note that in this instance, the coding requirements would be more demanding, and the execution time would be longer. The memory requirements remain about the same.

The above approaches were outlined in the text, Practical Aspects of Computational River Hydraulics, by Cunge, Holly, and Verwey, and were brought to our attention by Dr. Strelkoff. Prior to the discovery of these methods, the author investigated the use of general purpose sparse matrix routines. With submergence at branches, and/or with loops, then the Preissmann scheme yields a matrix only roughly similar to the five banded matrix described above. The difference is (first) the addition of node coefficients which are scattered throughout the upper triangular matrix. Secondly, the grid point coefficients no longer reside within a convenient five band field. A schematic representation of a simplified looping network, and the resulting matrix, is presented in Figures 1 and 2. With respect to Figure 2, note the main diagonal (the coefficients of which are underlined) and the tendency of the grid coefficients to meander slightly away from the central five bands.

The advantages of using established sparse matrix routines are several. First, they are off-the-shelf items, and (presumably) bug free. Secondly, in the case of non-linear systems of equations, convergence can be pre-determined and mathematically assured. Although there is a place for engineering ingenuity, in this instance a mathematically conclusive approach would be in the best interests of the project. Finally, although the sparse matrix routines are not as efficient as the double-sweep routines, the number of operations required are still roughly proportional to N, instead of N cubed.

Several possibilities were looked into. First, Harwell offers the MA28 series sparse matrix routines. These provide ease of use, relatively minimal storage requirements, and set-up routines which speed multiple solutions of similarly structured matrices (useful when solving non-linear sets of equations iteratively.) Secondly, Dr. Jeppson modified an early version of the MA28 source code. He streamlined the front-end, added a few short-cuts to the algorithmic core, and thus significantly enhanced the package. Third, the strongly implicit (SIP) method may offer an efficient solution in this case. Finally, due to the somewhat symmetric structure of the resulting sparse matrix, it may well be possible to develop a sparse matrix routine specifically for this case, and thus improve on the more general approaches. Of course, it appears that the enhanced double-sweep algorithms described above are precisely this approach, and are likely the optimum solution from an algorithmic point of view.

Several time trials were run, whereby different approaches were checked in an environment which was thought to be roughly similar to the proposed model environment. The time trials included an investigation of different computer languages and compilers. The results are included in the section on HARDWARE AND SOFTWARE CONSIDERATIONS.

MODELING GATE AND STRUCTURE HYDRAULICS AND CONTROLS

The need for hydraulic structure modeling is limited to two main areas of interest, in terms of the immediate goals for the proposed model. First, the model must provide for the existing hydraulic structures. These include various gate/check structure designs, of which there are about a half dozen standard implementations; the siphon structures used to convey water under roadways, stream beds, and the like; and finally, farm turn-out structures. In connection with this area of interest, the proposed model must be of modular design such that additional hydraulic structures may be modeled and easily included.

Secondly, the model must provide sufficient accuracy for the useful simulation of various canal operation schemes. This is in contrast to the more stringent requirements of a real-time control system. The idea that reasonable replications of hydraulic structure flow responses are adequate--reasonable in the sense that the model allows the exploration of management options--is admittedly a fuzzy specification. But, there are currently available several hydraulic models of real-time quality, with well researched model coefficients, which apply to the hydraulic structures existing within the proposed environment. These models are of sufficient quality that a close fit could be constructed based on research data alone, without resorting to field calibrations. For the purposes and goals of this project, no additional investment in hydraulic structure model quality was seen to be necessary. If future model requirements are such that the structural models and/or coefficients must be fine-tuned, then changes or upgrades could be made accordingly.

There are various means by which hydraulic structures may be categorized. These schemes allow a methodical approach to the development of hydraulic structure models. They also provide a practical means for creating model inventories within the code itself. It did not appear necessary to investigate these schemes in depth at this stage in the model development. Acknowledging that such approaches would be useful in the future was thought to be sufficient for the present. The current model environment is simply not complex enough, either in levels of branching or in types of structures, to warrant a more detailed investigation.

The model must allow for additional, in-house subroutines that implement one of several existing schemes providing feedback control of gate movement, based on measured water levels in adjacent pools. This requirement means there must be access to the source code, rather than simply an executable version, since there must be complete, real-time access to flow depths at any point and at any time increment, and possibly access to intermediate values during solution convergence.

HARDWARE AND SOFTWARE CONSIDERATIONS

Hardware Options: Review of hardware was necessarily limited to the existing hardware options of the various entities related to this research.

If the model is to be developed in-house, the primary workhorse for both coding and initial testing would be a personal computer of the PC-AT class. For final model development and implementation, the primary machine would be the DEC Micro-VAX. Secondary usage is expected on a PC-AT compatible. It is certain the model will be too large to fit within the current MS-DOS limit of 640k. Even with the release of an operating system such as OS/2 that will break the 640k barrier, the Micro-VAX would provide a more suitable environment in terms of overall speed and wherewithal. However, the use of personal computers for modeling network sections would be useful in the field.

Alternatives, for a reasonable additional cost, include sophisticated enhancement cards for the AT's, such as the Definicon series, or the use of 80386 machines. These options need not be considered at present, since the PC-AT/Micro-VAX combination provides more than sufficient utility for the project at hand. In time, options of this nature will improve significantly, and therefore ought to be considered when a model is available for implementation.

Software options: Various computer languages and compilers are available for the coding of this model. Existing models are generally written in FORTRAN, with a few exceptions (one is written in Basic, and another in Pascal.) The language C is becoming a worthwhile, if not superior alternative to FORTRAN. For instance, the engineering department at Arizona State University no longer teaches FORTRAN to incoming students--in their estimate, the language of choice for engineers is now C. Other knowledgeable sources point to MODULA 2, in that theoretically both FORTRAN and C are "low-level" languages, pascal is a "mid-level" language, and MODULA 2 and ADA, for example, are "high-level" languages. The subject is controversial.

Briefly, the advantages of FORTRAN are exceptional execution speed for mathematical algorithms, portability, and an existing base of engineers who are intimately familiar with the language. The advantages of C include provision for structured language elements, greater portability, improved access to machine hardware, execution speeds comparable to FORTRAN, and less overhead in terms of the size of the executable version. MODULA 2 may be the language of choice in the future, due to provisions for the use of multiple processors and other considerations beyond the scope of this report.

Table 1 below includes results from a number of time trials using different compilers that were available. The trials were originally run to determine if the general purpose sparse matrix routines would provide a reasonable alternative to recursive routines available for banded matrices. All tests were run on a PC-AT compatible with an 8 MHz CPU and a 6 MHz math coprocessor.

The wealth of experience with FORTRAN makes this language a strong contender. However, two advantages of the C language ought to be considered seriously. The foremost advantage, in the author's opinion, is the structured language elements available within C. A model of the proposed scope will require extensive bookkeeping--perhaps 90% of the code will exist solely to manage non-computational aspects of the model, with only 10% consisting of intense, computational algorithms for which FORTRAN is ideally suited. Secondly, Borland's Turbo C package (or Microsoft's Quick C when available) provides an extremely favorable programming environment which should reduce development time substantially. The only concession would be the use of reduced data sets while on the PC, a reasonable approach in any event.

CARIMA AND HYDRA MODELS

Two models are exemplary in terms of the proposed research environment--the HYDRA Network Model from Flow Science, and the CARIMA Network Model from SOGREAH.

HYDRA Network Model: The HYDRA model currently provides for both tributary and distributary branching, and for loops, where both distributary branching and looping require a proprietary, iterative scheme that reportedly converges rapidly. It is not yet clear if their convergence scheme is an engineering "this then that" approach that simply works, or if it is based on mathematically sound convergence criteria.

Regarding the approach to branching and looping detailed in the text, Practical Aspects of Computational River Hydraulics, Flow Science found the techniques as described to be theoretically plausible, but (practically speaking) not really workable. In the instance of downstream branching, the solution developed by Flow Science requires an iterative approach--they consider use of the double-sweep algorithm over the whole network to be inappropriate. In the instance of loops, they again use an iterative scheme. In their experience, use of the double-sweep algorithm in conjunction with a matrix of node information resulted in a matrix with substantially more coefficients than just the number of junction points; and furthermore, the resultant matrix was poorly conditioned so that generating reliable solutions was found to be problematic.

Their transient flow analysis is based on the full hydrodynamic equations and utilizes the Preissmann scheme; their network analysis is based on a double-sweep matrix solution algorithm with modifications as outlined above. Hydrodynamically isolated portions of the network are automatically isolated and solved independently by the network algorithms. Supercritical flows are detected, and are usually handled as single elements, rather than modeled using the implicit finite difference scheme. Momentum considerations are currently ignored when modeling canal outflows.

Flow Science claims (in their literature) the primary purpose for their model is flood wave analysis, and hence allow for the modeling of flood conditions such as overflow onto flood planes and into side channels. Secondarily, it is claimed the program can be used for modeling simple backwater curves, as an aid to channel design. In other words, it appears their model handles conditions inherent to river hydraulics, but it is not clear their model will properly handle (by virtue of experience as well as design) conditions unique to canal hydraulics and related hydraulic control structures. Because the model has not been developed to handle all elements of the proposed environment, various potential problems remain. Most notably, boundary condition and instability problems must be considered unresolved, unless the model has been designed and tested for the hydraulic conditions which are known to exist in the given environment.

A price of roughly twenty thousand dollars includes source code, full documentation, and customization of software to client specifications. The price could be more, depending on the number of program modules required and the degree of customization necessary to insure the code is usable within the clients (foreseeable) environment. The cost can be reduced by two thirds if only an executable version is desired. As a final note, the source code is written in FORTRAN 77, screen graphics are available, and the minimum hardware requirements would be an IBM PC-AT with a sophisticated enhancement card to speed numerical computations.

The CARIMA Network Model: Considerably more information is currently available to the author about the CARIMA model than any of the other models. An extensive list of pertinent issues was discussed with Dr. Holly. His answers were thought to be very thorough. These issues and Dr. Holly's responses are outlined following a general discussion of the model capabilities.

The CARIMA model employs the Preissmann scheme and the double-sweep banded matrix algorithm for both tributary/distributary branched systems and looped systems. The scheme for adapting the double-sweep algorithm to branched and looped systems is described (as noted earlier) in the book, Practical Aspects of Computational River Hydraulics, of which Dr. Holly is joint author. When questioned about the soundness of the computational techniques and the difficulties encountered by Flow Science (and, incidentally, the author) when applying the algorithms as described, Dr. Holly noted that the book was written at a time when SOGREAH was very protective of their proprietary rights to the technology. Hence, the descriptions are lean and simplistic when it comes to the practical understandings required to implement the concepts within a working model. He assured the author that the concepts were indeed valid, and that they were utilized within the CARIMA code. Additionally, the code is written so that network input is "user friendly." The algorithm is designed to digest random input of node information. For example, if after the initial input, the user were to input a reach creating a loop, this would present no problem.

The model can successfully handle (within about a centimeter of flow surface elevation) transitions from submerged flow to unsubmerged flow (and visa versa) at gates and weirs. This was indeed a problem during model development, but Dr. Holly notes they have successfully resolved this.

Numerically induced oscillations in flow can be handled by making the theta coefficient in the Preissmann scheme large (i.e. close to 1). This results in less second order accuracy and hence more smoothing. In their experience, a theta value near 0.5 (the optimum value in terms of accuracy) has never been needed. Finally, program filtering is fairly easy.

Filling of dry or ponded reaches presents no problem. In situations where this would result in a less accurate solution, one has the option to use additional iterations after the Preissmann scheme initial iteration.

Moving hydraulic jumps present difficulties. Dr. Holly reports that there is no known algorithm that can automatically solve this problem. However, he feels he can handle this situation, and in fact is currently seeking funding to support research in this area. Isolated portions of a reach with a hydraulic jump can be handled by the CARIMA model, if the reach portion is small enough to limit storage.

In response to a question concerning the high density of control structures typically found in irrigation distribution systems, Dr. Holly noted that a similar model, called CARIDOS, was developed for the City of Paris sewage system. The system consists of multiply connected sewage reaches with both free surface and pressurized flow. The CARIDOS model has been in continuous use over a number of years, and must handle a control structure density at least as great as anything expected within this project. In any case, one can implement a smaller computational grid spacing if needed. Also, with use of the Preissmann scheme, there is an inherent flexibility in that control structures can occur anywhere.

Regarding modeling of control structures and automatic canal control schemes, the CARIMA model currently provides several options. Perfect regulation of either flow or head can be accomplished through forcing the computational algorithms, and is available as an option to the user. PID controllers can be modeled. "Mixed hydraulic" gates, Nerpic gates, and constant (head) difference gates can be modeled. It was the author's understanding that user-defined control gates can be implemented with access to water levels, velocities, etc. Dr. Holly felt that, in his experience, some of the gate implementations might be too specific for our environment, but that any gate is considered a computational reach, and thus can be programmed as needed.

The program can only be used in batch mode--an interactive mode (the approach typical of modern applications) is not currently available. The program is designed in three parts. The first section handles pre-calculations. The second section handles time dependent calculations and generates the output files. The third section handles graphics. Dr. Holly suggests that the batch mode implementation of the program could be changed.

The current CARIMA code is about six years old--in other words, there have been no substantial changes in that time. The code is written in the FORTRAN language and was originally implemented on the IBM 360. There is some IBM assembly language--principally for a matrix inversion routine, but also for other minor routines. All these assembly routines have FORTRAN backups. It has been ported to the VAX by SOGREAH, but it has not been adapted for use on personal computers. The code uses the concept of "dynamic memory" such that there is no maximum limit on the size of any vector variable (or any other limitation of this type typical to FORTRAN). There must be, of course, a predefined limit on the total amount of memory allocated to the model. Finally, there is a batch graphics capability, which utilizes (through modifications developed by Dr. Holly) the DISSPLA graphics package.

The model cost is determined by intended use. Specifically, if it would be used to compete with the parent company, the cost understandably would go up. Dr. Holly suggests that CARIMA has long since paid for itself, and that the parent company would be interested in indirect benefits such as might be accrued through exposure of CARIMA to the professional community. An estimate of ten thousand dollars was suggested as a ball park figure (he was assuming that the ARS would be purchasing the program.) This includes the source code. (Apparently, executable versions of the model are not sold.) Formal training in use of the model would be insisted upon by the parent company. Typically such training is given in France, but Dr. Holly feels that all training could be provided at Iowa City. It should be noted here that he has about two thirds of the operator's manual translated into English. The complete manual is available only in French.

Dr. Holly discussed the difficulty to expect when writing such a program from scratch. He reports that, fundamentally, the technology involved is not new. (In the author's experience, the technology--practically speaking--is either new or untested within the U.S. technical community, with the exception of a handful of people.) However, writing a flexible, fully adaptable model, such as CARIMA, would involve a substantial undertaking. With experience, a model specific to a given site could be written in less than two months. From scratch (i.e. without experience), he claims such a site-specific model could be written in six months. He teaches a computational hydraulics course at the University of Iowa, in which the fundamentals of this technology are taught.

If interest in the CARIMA model is sufficient to warrant further investigation, one could either visit Dr. Holly at Iowa City and test the model there, or conceivably one could test the model via a modem. Any such model testing would be free of charge, and Dr. Holly would offer assistance to the extent he is able. He feels such testing is crucial for any realistic evaluation of the model.

CONCLUSIONS

Aside from financial considerations, it appears that the CARIMA Network Model from SOGREAH will provide the optimum performance in terms of the research needs of the ARS. Additionally, it appears to be the best starting point for a more user oriented model suitable for use by a typical irrigation district. Note, however, that further investigation of the CARIMA model is in order, since the ultimate investment in time and resources will be substantial before this (or any other model) is fully functional for a given research station. There is no substitute for hands-on experience.

The primary reason for selecting the CARIMA model over the others, or in lieu of in-house model development, was the thoroughness of the responses given by Dr. Holly to the many questions posed by the author. Obviously, this is a subjective criteria, but it is felt to be significant. No other model developer had nearly the command of the subject at hand as did Dr. Holly--noting this, other reasons follow.

The primary thrust of ARS research is not hydraulic model development, but utilization of such a model to investigate conditions peculiar to agricultural usage of water resources. In light of this, model development would be a costly and demanding item in the category of "overhead," unless it was obvious and could be shown that no such model exists. It appears that the CARIMA model has the technical wherewithal to handle the proposed research environment. If a model test indicates no further problems, then justification of in-house development would be just about impossible, in the author's opinion--the primary motivation for this conclusion being the spector of "hidden costs." The author has found that within the U. S. technical community, both experience and practical understandings are lacking in this particular area of hydraulics. Making up the difference in these dimensions usually proves to be costly. There are a number of people capable of working their way from sound theoretical understandings to a working model, but there is little to justify their doing so from the point of view of ARS research needs. It would just simply be prudent to take advantage of this existing model.

Modifications to the existing code might be time consuming, but not difficult in that the code is in FORTRAN, and presumably no modifications would need to be made to the essential hydraulic or network algorithms, or to the essential data structures. The modifications envisioned by the author would be fairly straight forward: items such as modifying hydraulic structure algorithms, porting the program to other hardware, or (at some future time) adding a "front end" to make the package interactive. Modifications beyond this would likely require the expertise of the program author. In this regard, it is likely that the expertise of Dr. Holly would suffice, in that he is intimately familiar with the model, this particular dimension of hydraulics appears to be within the core of his professional career, and he resides within the U. S. and is available.

The CARIMA model uses state-of-the-art technology when it comes to modeling both unsteady flow and networks. This seems odd in that the model is nearly a decade old, but more recent efforts have not resulted in a superior model, in the author's opinion. Hydraulic structure modeling and automatic gate control seem reasonably within the scope of the model, as it exists now. It may be that initial modifications would be primarily in this area, but it is felt that such modifications would be minor.

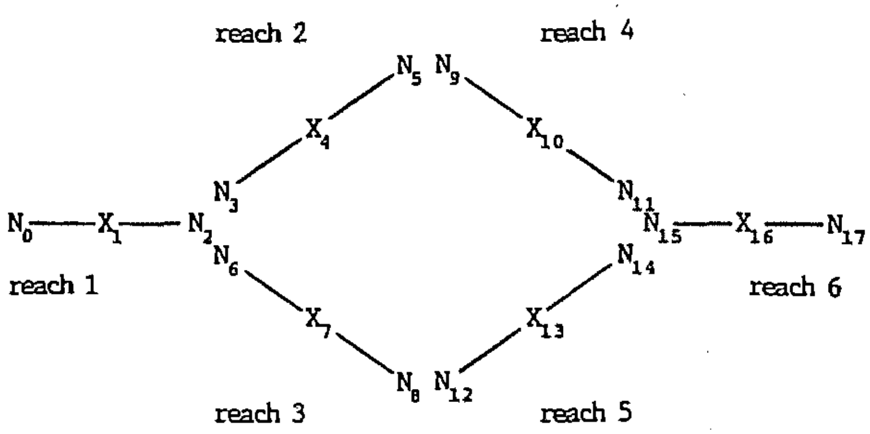
Since the package has already been ported to the VAX by SOGREAH, it would seem likely that the model could be used immediately by the Water Conservation Lab in Phoenix on their micro VAX. The use of graphics would require the DISSPLA graphics package. For research, the model would suffice nearly as is. For use on a personal computer, additional work would obviously be necessary.

In conclusion, the CARIMA package is the optimum choice based on the author's investigations. It is recommended that further consideration be given to the HYDRA model--a demo disk was promised to the ARS by Flow Science, but did not arrive in time for this report. It is further recommended that prior to serious consideration of either the CARIMA or HYDRA model, a series of tests be implemented to determine if claims made by the model developers are justified, and to insure that the research needs would be met.

PERSONNEL: John Parrish, Albert J. Clemmens

Table 1. Results of time trials conducted using a simple finite difference problem which required the solution of a tridagonal matrix of order 2000.

Compiler	Solution algorithm	source size	execution time	executable size	Memory required
MS FORTRAN	Harwell sparse	76,335	4:41.60	107,341	441,242
MS FORTRAN	Tri-diagonal recursive	4,939	0:41.85	42,447	91,390
Turbo Pascal	Tri-diagonal recursive	5,885	1:53.59	13,322	?
Turbo C	Tri-diagonal recursive	4,446	0:47.00	11,789	?



N - Grid points at network nodes.
X - Grid points along reach interior.
1,2,3,etc. - Grid point numbers (subscripts).

Figure 1. This is a schematic of a simplified network with one distributary branch, one tributary branch, and one loop. There is only one interior grid point within each reach.

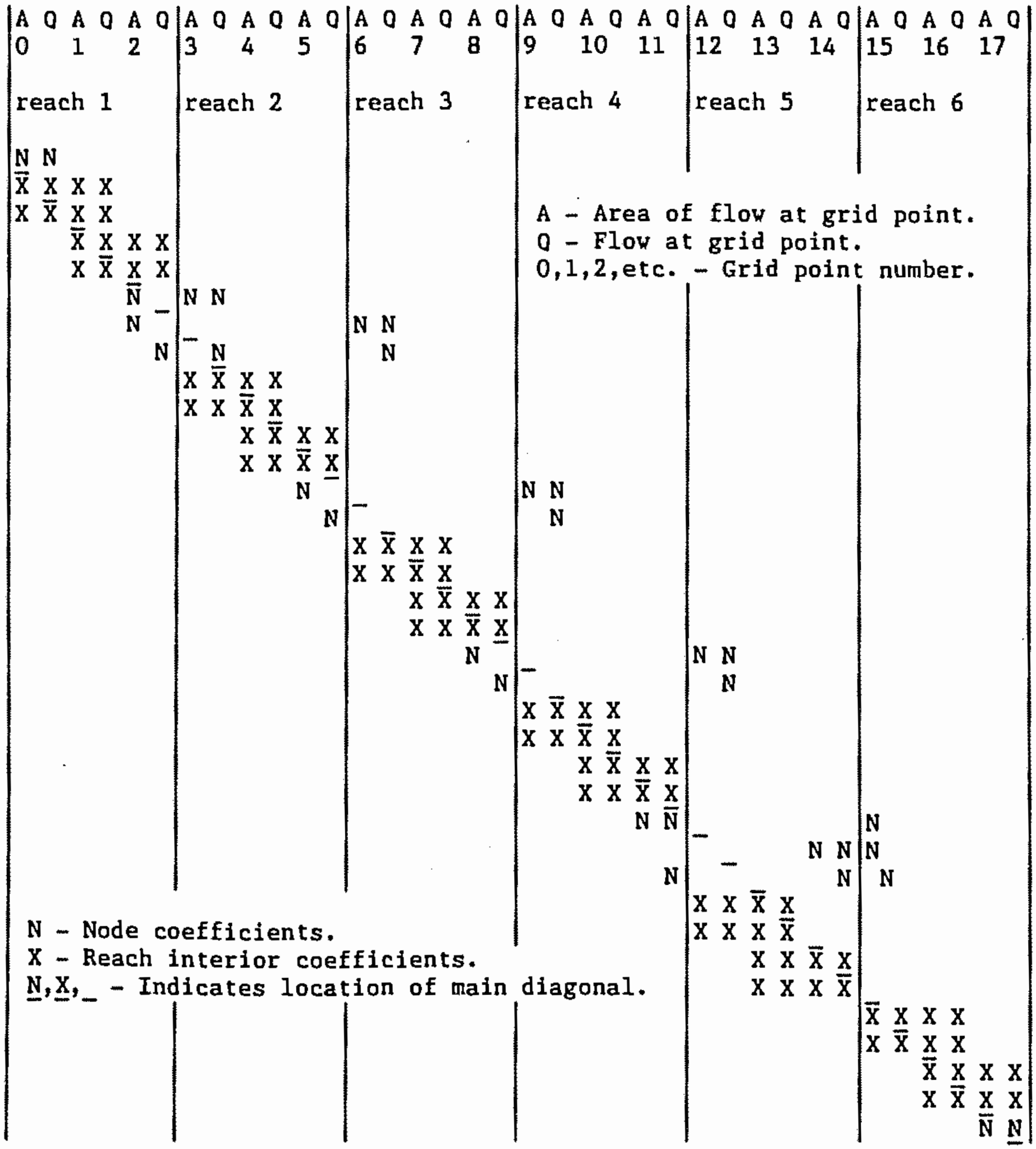


Figure 2. This is a schematic of the non-zero coefficient locations in a sparse matrix derived from the simplified network shown in Figure 1.

TITLE: SURFACE-DRAINING LEVEL FURROWS

SPC: 1.3.03.1.f CRIS WORK UNIT: 5344-13000-001

INTRODUCTION

Traditionally level basins, either flat planted or with furrows, are irrigated by turning a desired volume of water into the basin where it is confined until infiltrated. By configuring the water supply channel properly in relationship to the basin surface, some of the applied water can be drained from the inlet end of the basin after the irrigation advance is complete. A series of field studies were conducted to quantify this surface drainage phenomenon. The studies will provide a data base for hydraulic model verification and guidelines for designing and managing such systems. The specific procedures used in the field studies were outlined in the 1986 Annual Research Report. Herein will be presented some of the important data analyses results from the studies.

TESTS CONDUCTED IN 1986 AND 1987

A test site was established at the University of Arizona's Maricopa Agricultural Center on their field plot number 11. The field was precisely leveled by the University using their laser-controlled scraper. The standard deviation of the field elevations taken over the finished area (60 m x 360 m) used for the level furrow study was 6.0 mm, which is considerably better than most "precisely" leveled basins. The area was furrowed out immediately after leveling, establishing relatively deep furrows on 1.02 m (40 inch) centers. Once the test furrows were established, a drainage channel to be used to hold the drainback from the level furrows, was constructed across the end of the furrows. The maximum working length of the test furrows was 354 m after the drain channel was established and space was allowed for the test trailer.

A series of 18 furrows were selected for test purposes; 6 each at 120 m, 240 m, and 354 m long. Each furrow was "irrigated" three times--Dry (soil moisture conditions as they were found at the time of the test), Wet 1 (2 days after the first test), and Wet 2 (about one week after the Wet 1 test). No crop was being grown on the plots. Three identical sets of monitoring equipment had been developed so three furrows were evaluated at the same time (any one day). Any daily test would include one furrow from each of the three lengths. The tests conducted differed only in inflow rate, criteria for inflow cutoff, and whether or not surface drainage was allowed. The specific setup conditions are shown in Table 1.

DATA ANALYSIS

Computer programs were developed to analyze the field data. The first program (KRUSH), with an original version (KRUNCH) finished in 1985, provided the initial data reduction. KRUSH used six input files including input from the Easy Logger.

XDIS: Distances to monitoring stations along furrow.

VLT***[1]: Transducer output voltages from the EasyLogger for atmosphere, the reference double-bubblers, outlet flume, and the bubblers from each furrow station.

HPF***: Elevation readings for each furrow--5 rod readings at each station, 4 of the bottom of the furrow near each station and 1 on the top of the bubbler cup.

FLM***: General description of test, clock synchronization (watches and Easy Logger), outflow flume calibration check, and point gauge readings on both the inflow and outflow flumes.

XSA***: Furrow cross-section measurements at each station for each furrow.

TARE: Distance of bubbler below top of cup for all cups used in the study.

Output files from this program included:

F***++[2]: Water depth and time (hydrograph) for each station.

QRO***: Flow rate data (inflow vs. time and outflow vs. time).

STA***: Furrow cross-sectional characteristics for each station along with station elevations. This includes best-fit power function terms for both furrow width vs. depth and wetted perimeter vs. depth.

In most cases the logging system provided high quality station hydrographs, Fig. 1, but occasionally the hydrographs were not smooth, Fig. 2. The spurious data were likely caused by some irregularities in the logging system. Hence a portion of the hydrographs required smoothing for use in later analyses. The solid plotting points of Figs. 1 and 2 resulted from smoothing the F***++ files (open points of Figs. 1 and 2). The curve smoothing was done using the "curve approximation" method provided as part of the GRAFIT program on the HP-1000. Parameters of the Curve Smooth routine were modified until the generated curve "looked right." New hydrograph files (S***++) were then generated and were used in later analyses. All F***++ files were smoothed, for data processing simplicity, even though the original quality might have been high, Fig. 1.

Station elevations were corrected for surveying equipment error. The correction applied (-5.25 mm per 30.48 m) was determined from peg tests. The STA*** file was regenerated with the uncorrected and corrected elevations included.

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[1] ***Refers to Test Number

[2] ++ Refers to Station Number

A second program (PROFL) used the new S, corrected STA, and QRO data files to develop water surface profiles for the furrow at each time the advancing water reached a test station . Additional information developed included irrigation advance time, furrow cross sectional statistics (depth related to top width and wetted perimeter), shape factor statistics, and various statistics describing the inflow and outflow (surface drainage). These data, outputted from the PROFL program, were stored in files named FPR***. The FPR*** files, for the 54 furrow studies, are shown as Tables 2 through 55 and are recorded in the Annual Research Report as a data base for later use.

A third program used the FPR*** files to estimate empirical infiltration parameters from volume balance calculations during advance. It was assumed that infiltration at any location along the furrow was characterized by a Kostiakov power function. A number of options were available for relating infiltration to furrow geometry and were presented by Clemmens in the 1984 Annual Research Report (pp. 68 - 79). Infiltrated depth along the furrow (expressed in terms of furrow spacing) and statistics associated with the infiltrated water distribution were calculated once the infiltration parameters had been estimated. Additional information dealing with water volume in the furrow throughout the irrigation were useful in looking at volume drained from a furrow relative to volume present at the time drainage started.

SUMMARY

Draining a portion of the applied water from the inlet end of a level furrow can potentially lead to smaller applications per irrigation and the applied water can possibly be more uniformly applied than with non-draining basins. In many instances small applications are desirable to maintain high efficiencies (limited water holding capacity of sandy soils) and optimum soil, water, and air conditions for plant growth (low final intake rates on heavy clay soils can cause serious aeration problems). A field study was completed to quantify this surface drainage phenomenon for level furrows. Eighteen furrows were irrigated three different times to determine water advance, recession, and water depth at selected sites along a furrow. The characteristics of each furrow and each irrigation (advance, recession, water depth at selected sites along a furrow, furrow cross-section, etc.) were precisely measured. Factors that were varied from test to test included furrow length, inflow rate, gross water applied, antecedent soil water, and drained and nondrained conditions. The water surface profile data for each of 54 individual furrow tests were summarized.

PERSONNEL A.R. Dedrick, A.J. Clemmens

Table 1. Irrigation conditions for surface-drained level furrow study. Each setup represents a total of nine tests (three furrow lengths each irrigated three times). Setup 6 was completed without surface drainage.

Field Test Setup	Nominal Inflow Rate (1/s)	Inflow Cutoff	Furrow Length (m)	Test Number Identification DRY	WET1	WET2
1	4	When advance reached end of furrow.	120	101	104	107
			240	102	105	108
			354	103	106	109
2	4	When advance reached end of furrow.	120	110	113	116
			240	111	114	117
			354	112	115	118
3[1]	3	When advance reached end of furrow.	120	119	122	125
			240	120	123	126
			300	121	124	127
4	4	10 min. after advance reached end of furrow.	120	128	131	134
		20 min. after advance reached end of furrow.	240	129	132	135
		30 min. after advance reached end of furrow.	354	130	133	136
5	4	10 min. after advance reached end of furrow.	120	137	140	143
		20 min. after advance reached end of furrow.	240	138	141	144
		30 min. after advance reached end of furrow.	354	139	142	145
6	4	When advance reached end of furrow.	120	146	149	152
			240	147	150	153
			354	148	151	154

[1] Long furrow shortened to 300 m due to slow advance time.

Table 2. Water surface profile data for Test Number 101, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 101

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	13	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	17.02	23.43	14.35	14.69	9.80	0.00	6.73	8.82
*****TOP WIDTH*******								
R^2	.980	.956	.980	.969	.974	.948	.993	.990
*TW=A(D)^B * A	25.782	52.246	38.970	23.276	34.982	24.692	11.508	21.570
TW & D, MM B	.618	.465	.525	.623	.544	.610	.778	.656
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	25.736	52.042	38.754	23.198	34.786	24.572	11.604	21.496
WP & D, MM B	.628	.473	.535	.636	.554	.624	.794	.669
SURF. SHAPE FACT.								
*PROFILE *	.179	.243	.257	.361	.839	.270	.385	0.000
*DEPTH *	.114	.155	.164	.231	.536	.195	.209	.070
*ADVANCE *	.639	.639	.639	.639	.639	.724	.543	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.07	3.500	0.000	2.2	0.0						
.22	3.941	0.000	6.4	5.4	0.0					
.65	3.941	0.000	19.0	16.0	15.8	0.0				
1.23	3.939	0.000	35.9	30.1	29.8	26.4	0.0			
8.92	3.868	0.000	99.8	90.0	92.5	91.4	85.2	0.0		
15.62	3.831	0.000	106.5	97.3	100.7	101.2	97.4	86.6	0.0	
26.52	3.778	0.000	83.2	80.6	88.5	96.2	97.6	106.2	92.2	0.0
30.00	-2.512	0.000	55.5	53.5	60.8	69.2	72.2	87.3	86.4	81.6
40.00	-.547	0.000	36.8	30.5	36.6	42.4	43.2	56.7	55.7	52.9
50.00	-.077	0.000	19.8	13.9	19.5	24.5	26.5	37.2	36.4	30.8
60.00	-.014	0.000	0.0	0.0	.1	3.5	5.4	17.3	16.3	8.3
69.60	-.007	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 49.90 MM M2/M/M
DRAINBACK VOLUME = 7.51 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.846 L/S
INFLOW TIME = 26.37 MIN
AVE. SLOPE = -.00011 M/M
AVE. TOP WIDTH A = 27.277
AVE. TOP WIDTH B = .598
AVE. WET PERIM A = 27.074
AVE. WET PERIM B = .611
AVE. SHAPE PROF = .362
AVE. SHAPE DEPTH = .209
AVE. SHAPE ADVAN = .518

Table 3. Water surface profile data for Test Number 102, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 102

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	19	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	44.42	33.81	29.21	37.51	36.32	67.29	76.25	20.27	21.00	10.29	30.04	0.00
*****TOP WIDTH*******												
R^2	.978	.988	.983	.989	.986	.941	.978	.988	.988	.995	.991	.991
*TW=A(D)^B * A	28.110	11.706	15.466	9.062	17.716	25.558	19.772	6.270	17.486	9.432	14.876	6.530
TW & D, MM B	.601	.769	.712	.827	.670	.597	.646	.896	.674	.808	.727	.880
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	28.022	11.804	15.484	9.240	17.650	25.414	19.720	6.564	17.436	9.578	14.892	6.806
WP & D, MM B	.611	.785	.727	.842	.687	.610	.660	.909	.691	[illegible]	.742	.895
SURF. SHAPE FACT.												
*PROFILE *	.743	.524	.839	.445	.354	.373	.251	.233	.558	.595	.390	0.000
*DEPTH *	.322	.227	.363	.193	.154	.224	.237	.199	.424	.453	.263	.245
*ADVANCE *	.433	.433	.433	.433	.433	.601	.942	.853	.759	.761	.675	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.09	3.576	0.000	5.8	0.0										
.44	3.941	0.000	28.6	39.4	0.0									
2.20	3.941	0.000	57.6	80.9	66.9	0.0								
5.61	3.935	0.000	84.0	106.7	107.8	94.4	0.0							
12.55	3.917	0.000	108.6	131.4	129.7	120.5	110.2	0.0						
24.65	3.891	0.000	120.5	143.9	146.2	135.9	132.2	98.1	0.0					
33.45	3.886	0.000	124.7	147.7	150.2	139.9	136.1	100.3	55.8	0.0				
43.45	3.894	0.000	126.6	149.9	152.2	142.1	138.3	102.4	68.8	114.3	0.0			
55.25	3.940	0.000	128.6	151.8	153.9	143.7	140.3	104.2	74.2	120.9	85.6	0.0		
67.65	3.989	0.000	130.1	153.3	155.5	145.3	141.9	106.6	78.3	123.7	96.4	85.7	0.0	
82.45	3.997	0.000	132.1	154.0	158.1	147.8	143.3	107.4	81.2	124.2	102.0	96.9	58.6	0.0
90.00	-1.322	0.000	50.5	73.4	79.6	78.8	85.6	67.2	61.8	115.6	106.9	103.0	76.1	84.0
100.00	-.788	0.000	30.9	54.2	56.7	49.1	52.1	32.3	29.5	84.5	82.2	89.7	61.2	84.7
110.00	-.073	0.000	19.0	42.4	44.9	36.9	35.8	11.9	11.9	67.0	62.0	68.7	37.8	61.1
120.00	-.027	0.000	6.1	29.5	32.3	25.2	20.3	0.0	0.0	50.8	44.3	51.3	19.6	45.6
130.00	-.026	0.000	0.0	14.9	17.6	13.0	2.0	0.0	0.0	28.7	23.3	27.3	3.8	21.1
140.00	-.025	0.000	0.0	.0	4.5	.5	0.0	0.0	0.0	5.9	3.0	2.3	0.0	0.0
145.20	-.024	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 82.78 MM M2/M/M
DRAINBACK VOLUME = 7.89 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.939 L/S
INFLOW TIME = 85.42 MIN
AVE. SLOPE = -.00013 M/M
AVE. TOP WIDTH A = 13.988
AVE. TOP WIDTH B = .729
AVE. WET PERIM A = 14.007
AVE. WET PERIM B = .745
AVE. SHAPE PROF = .482
AVE. SHAPE DEPTH = .275
AVE. SHAPE ADVAN = .581

Table 4. Water surface profile data for Test Number 103, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 103

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	24	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	32.19	19.33	9.97	0.00	1.28	16.38	16.50	30.15	27.50	32.38	22.22	24.09	14.74	8.34	17.47	7.53
*****TOP WIDTH********																
R^2	.976	.978	.988	.972	.922	.972	.930	.954	.972	.979	.996	.983	.996	.988	.993	.962
*TW=A(D)^B * A	64.910	9.740	8.196	12.422	63.070	7.712	8.174	35.660	14.854	28.692	4.380	29.852	10.108	14.230	5.344	27.736
TW & D, MM B	.434	.819	.850	.763	.429	.864	.828	.543	.731	.617	.952	.586	.791	.714	.908	.582
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	64.782	9.902	8.404	12.498	62.640	7.940	8.366	35.412	14.894	28.616	4.812	29.720	10.232	14.248	5.692	27.510
WP & D, MM B	.439	.833	.864	.778	.438	.878	.846	.554	.744	.626	.962	.537	.809	.732	.923	.596
SURF. SHAPE FACT.																
*PROFILE *	.317	.358	.274	.459	.350	.565	.259	.608	.259	.284	.246	.481	.307	.361	.526	0.000
*DEPTH *	.121	.136	.104	.175	.133	.361	.187	.344	.167	.156	.147	.262	.144	.226	.270	.457
*ADVANCE *	.382	.382	.382	.382	.382	.639	.726	.566	.646	.547	.539	.546	.469	.628	.514	0.000

55.324 57.16
.4899 .4890

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.04	3.088	0.000	23.3	0.0														
.28	3.886	0.000	48.9	60.3	0.0													
1.53	3.886	0.000	56.0	69.4	40.9	0.0												
4.42	3.886	0.000	72.5	90.6	99.9	65.2	0.0											
9.58	3.886	0.000	84.4	105.2	107.1	104.8	93.8	0.0										
18.08	3.886	0.000	93.9	115.0	117.9	118.1	109.9	51.3	0.0									
26.88	3.882	0.000	99.6	121.0	123.6	125.2	118.1	106.2	91.4	0.0								
39.88	3.874	0.000	106.5	127.8	130.9	132.9	128.6	120.9	108.3	81.1	0.0							
52.88	3.865	0.000	110.4	131.5	134.9	137.3	134.3	127.0	115.7	95.0	75.4	0.0						
70.08	3.855	0.000	114.4	135.7	139.1	141.6	136.4	133.0	123.0	104.3	91.0	70.8	0.0					
87.58	3.853	0.000	117.0	138.7	142.0	144.6	139.3	136.8	127.2	109.1	96.9	78.5	71.8	0.0				
108.68	3.870	0.000	119.4	140.9	144.5	147.1	143.0	139.7	131.0	113.6	102.2	84.3	80.3	66.6	0.0			
136.08	3.870	0.000	122.0	143.5	147.0	149.8	145.3	143.0	134.2	116.7	107.4	89.9	89.1	90.6	73.2	0.0		
158.38	3.866	0.000	123.0	144.5	148.1	151.1	144.2	144.4	136.1	118.9	109.3	93.2	93.4	89.4	81.7	61.9	0.0	
181.58	3.917	0.000	106.8	124.8	128.7	134.9	129.0	140.7	135.4	118.9	112.7	96.0	99.4	84.5	86.6	73.2	54.8	0.0
190.00	-2.837	0.000	66.7	89.8	95.1	100.7	97.8	104.9	103.0	92.0	91.9	83.4	92.8	81.1	86.6	77.1	60.6	68.0
200.00	-.829	0.000	46.6	71.0	76.3	81.6	76.6	82.1	79.1	78.3	67.2	59.2	74.7	63.6	73.8	71.9	61.0	71.9
210.00	-.395	0.000	34.2	56.0	60.2	64.7	60.9	65.5	61.4	53.7	48.5	41.0	54.9	43.2	55.5	55.7	46.8	58.2
220.00	-.085	0.000	24.2	46.0	50.0	54.3	49.9	53.3	49.5	40.0	33.2	20.9	29.5	18.1	33.8	32.5	24.1	36.9
230.00	-.013	0.000	10.4	36.9	41.2	45.2	40.8	42.8	37.8	24.7	12.8	0.0	0.0	0.0	8.3	0.0	0.0	.6
240.00	-.009	0.000	.5	24.9	29.9	35.3	31.1	29.8	23.0	9.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250.00	-.006	0.000	0.0	11.1	18.9	26.3	17.0	15.3	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
275.60	0.000	0.000	0.0	4.0	12.5	21.0	2.5	7.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

```
INFLOW VOLUME     =  117.42 MM M2/M/M
DRAINBACK VOLUME =    6.27 MM M2/M/M
RUNOFF VOLUME     =    0.00 MM M2/M/M
AVE. INFLOW RATE =   3.875 L/S
INFLOW TIME       =  181.67 MIN
AVE. SLOPE        =  .00000  M/M
AVE. TOP WIDTH A =  17.088
AVE. TOP WIDTH B =    .633
AVE. WET PERIM A =  16.955
AVE. WET PERIM B =    .710
AVE. SHAPE PROF   =    .377
AVE. SHAPE DEPTH =    .212
AVE. SHAPE ADVAN =    .539 ^Z
```

Table 5. Water surface profile data for Test Number 104, Table 1.

```
MAC FURROW DRAINBACK STUDY NUMBER 104
    NO. STA      NO. TIME PERIODS   FURROW SPACING
       8               17                 1.016
                    STA 1  STA 2  STA 3  STA 4  STA 5  STA 6  STA 7  STA 8
      DISTANCE, M    0.0    5.0   10.0   20.0   30.0   60.0   90.0  120.0
   ELEVATIONS, MM  17.02  23.43  14.35  14.69   9.80   0.00   6.73   8.82
*****TOP WIDTH*******
              R^2   .980   .956   .980   .969   .974   .948   .993   .990
  *TW=A(D)^B *  A 25.782 52.246 38.970 23.276 34.982 24.692 11.508 21.570
  *TW & D, MM*  B   .618   .465   .525   .623   .544   .610   .778   .656
*****WETTED PER******
              R^2  1.000  1.000  1.000  1.000  1.000  1.000  1.000  1.000
  *WP=A(D)^B *  A 25.736 52.042 38.754 23.198 34.786 24.572 11.604 21.496
  *WP & D, MM*  B   .628   .473   .535   .636   .554   .624   .794   .669
**SURF. SHAPE FACT.**
  *PROFILE    *     .212   .368   .179   .230   .283  1.000   .338  0.000
  *DEPTH      *     .182   .316   .153   .197   .243   .444   .253  0.000
  *ADVANCE    *     .858   .858   .858   .858   .858   .407   .749  0.000

  TIME  Q IN Q OUT   HEAD
   MIN   L/S   L/S    MM

  0.00 0.000 0.000    0.0
   .30 3.777 0.000   30.5    0.0
   .80 3.886 0.000   63.6   38.7    0.0
  1.49 3.886 0.000   70.2   49.0   18.3    0.0
  2.39 3.886 0.000   78.8   62.4   42.0   36.5    0.0
  4.10 3.886 0.000   88.8   78.6   79.9   74.2   63.3    0.0
 11.10 3.897 0.000  100.8   91.4   94.7   94.5   90.8   82.5    0.0
 16.30 3.895 0.000   97.6   92.2   97.7   99.4   98.3   97.5   84.5    0.0
 20.00 -.723 0.000   60.3   58.6   66.3   74.2   76.3   92.5   88.1   81.0
 30.00 -.893 0.000   39.1   37.1   43.8   50.1   51.4   65.3   65.0   62.2
 40.00 -.278 0.000   28.8   26.8   32.9   38.6   38.7   50.9   49.0   48.4
 50.00 -.092 0.000   21.8   19.2   24.9   29.8   31.4   44.6   43.8   41.0
 60.00 -.028 0.000   15.5   11.3   16.9   20.3   21.4   32.1   30.5   25.0
 70.00 -.017 0.000   10.4    4.6    9.0   11.1   13.8   20.9   21.0   15.6
 80.00 -.012 0.000    5.3    1.1    3.9    4.4    7.0   10.7   11.2    7.8
 90.00 -.005 0.000     .3    0.0     .2    0.0     .6    1.0    1.2     .8
 91.20 0.000 0.000    0.0    0.0    0.0    0.0    0.0    0.0     .0     .0

    INFLOW VOLUME    =   32.94 MM M2/M/M
    DRAINBACK VOLUME =    9.56 MM M2/M/M
    RUNOFF VOLUME    =    0.00 MM M2/M/M
    AVE. INFLOW RATE =   3.891 L/S
    INFLOW TIME      =   17.20 MIN
    AVE. SLOPE       = -.00011  M/M
    AVE. TOP WIDTH A =  27.277
    AVE. TOP WIDTH B =    .598
    AVE. WET PERIM A =  27.074
    AVE. WET PERIM B =    .611
    AVE. SHAPE PROF  =    .373
    AVE. SHAPE DEPTH =    .224
    AVE. SHAPE ADVAN =    .816
```

Table 6. Water surface profile data for Test Number 105, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 105

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	25	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	44.42	33.81	29.21	37.51	36.32	67.29	76.25	20.27	21.00	10.29	30.04	0.00
*****TOP WIDTH*******												
R^2	.953	.976	.988	.964	.989	.970	.943	.993	.995	.994	.989	.994
*TW=A(D)^B * A	48.634	31.664	18.492	34.790	27.774	9.492	51.584	16.768	14.688	13.278	21.902	15.480
TW & D, MM B	.519	.574	.685	.557	.582	.787	.454	.704	.710	.744	.643	.710
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	48.494	31.502	18.482	34.640	27.610	9.636	51.298	16.766	14.692	13.320	21.828	15.496
WP & D, MM B	.525	.585	.698	.567	.595	.806	.463	.717	.727	.760	.656	.725
SURF. SHAPE FACT.												
*PROFILE *	.483	.423	.696	.442	.434	.324	.251	.211	.283	.236	.598	0.000
*DEPTH *	.250	.220	.361	.229	.225	.257	.188	.170	.238	.205	.529	.391
*ADVANCE *	.518	.518	.518	.518	.518	.794	.748	.805	.841	.866	.884	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.11	3.690	0.000	11.0	0.0										
.41	3.997	0.000	40.7	49.4	0.0									
1.58	3.997	0.000	52.6	74.2	54.3	0.0								
3.45	3.997	0.000	68.6	94.6	91.5	72.6	0.0							
7.80	3.997	0.000	91.0	115.9	112.0	101.3	94.7	0.0						
13.00	3.997	0.000	107.2	136.5	126.7	116.4	112.5	75.7	0.0					
19.10	3.997	0.000	118.0	147.4	137.9	128.0	125.1	89.3	51.1	0.0				
25.20	3.997	0.000	122.6	152.0	142.8	133.2	130.4	95.4	60.3	100.1	0.0			
31.30	3.997	0.000	124.7	154.2	145.4	135.8	133.3	98.9	68.9	113.7	76.2	0.0		
37.40	3.997	0.000	125.2	152.7	147.0	137.3	134.6	99.6	72.0	118.9	91.4	78.3	0.0	
43.50	3.997	0.000	127.4	149.2	151.8	140.7	137.4	102.3	76.1	121.7	100.5	94.1	51.6	0.0
50.00	-.744	0.000	44.1	78.8	87.0	86.6	94.7	80.1	67.3	117.0	104.8	107.0	78.6	77.2
60.00	-1.471	0.000	7.9	42.0	45.6	43.4	52.3	35.1	40.0	97.1	97.1	109.7	87.5	106.0
70.00	-.194	0.000	12.5	40.8	34.0	28.0	42.3	17.9	28.8	84.6	82.2	94.4	68.5	94.7
80.00	-.040	0.000	0.0	24.8	27.2	19.7	31.0	9.4	24.8	80.3	78.4	85.7	55.5	82.7
90.00	-.009	0.000	0.0	17.5	19.3	14.1	25.0	0.0	14.6	70.1	68.8	77.7	51.8	72.5
100.00	-.005	0.000	0.0	10.3	11.1	7.5	17.6	0.0	6.7	64.5	62.5	68.6	44.7	60.6
110.00	-.003	0.000	0.0	2.7	5.2	1.5	9.8	0.0	0.0	56.8	53.1	58.4	31.5	50.5
120.00	-.003	0.000	0.0	0.0	0.0	0.0	1.6	0.0	0.0	50.3	46.1	51.8	24.5	43.3
130.00	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	41.9	36.2	43.6	14.1	34.2
140.00	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.5	30.0	36.0	1.5	25.2
150.00	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.5	25.0	27.3	0.0	14.3
160.00	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	11.0	10.8	0.0	0.0
166.20	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.5	0.0	0.0	0.0

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INFLOW VOLUME     =  46.22 MM M2/M/M
DRAINBACK VOLUME  =   8.90 MM M2/M/M
RUNOFF VOLUME     =   0.00 MM M2/M/M
AVE. INFLOW RATE  =  3.996 L/S
INFLOW TIME       =  47.00 MIN
AVE. SLOPE        = -.00013  M/M
AVE. TOP WIDTH A  = 23.312
AVE. TOP WIDTH B  =   .630
AVE. WET PERIM A  = 23.120
AVE. WET PERIM B  =   .644
AVE. SHAPE PROF   =   .398
AVE. SHAPE DEPTH  =   .272
AVE. SHAPE ADVAN  =   .658
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Table 7. Water surface profile data for Test Number 106, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 106

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	29	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	32.19	19.33	9.97	0.00	1.28	16.38	16.50	30.15	27.50	32.38	22.22	24.09	14.74	8.34	17.47	7.53
*****TOP WIDTH*******																
R^2	.995	.991	.983	.979	.984	.976	.979	.955	.976	.998	.972	.998	.982	.996	.991	.993
*TW=A(D)^B * A	66.562	34.150	20.194	15.162	23.048	12.194	21.430	37.070	9.134	10.278	14.452	11.462	19.458	11.154	11.090	11.656
TW & D, MM B	.431	.556	.664	.727	.641	.774	.645	.554	.827	.807	.721	.765	.658	.781	.770	.754
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	66.386	33.956	20.112	15.180	22.954	12.285	21.340	36.874	9.306	10.424	14.478	11.552	19.374	11.266	11.188	11.948
WP & D, MM B	.436	.576	.678	.741	.653	.788	.659	.563	.842	.821	.737	.782	.673	.796	.787	.771
SURF. SHAPE FACT.																
*PROFILE *	.342	.351	.377	.364	.380	.627	.343	.381	.313	.555	.388	.349	.430	.134	.705	0.000
*DEPTH *	.161	.166	.178	.172	.179	.319	.226	.280	.226	.349	.244	.235	.305	.098	.461	.938
*ADVANCE *	.472	.472	.472	.472	.472	.510	.658	.736	.722	.618	.630	.673	.708	.736	.653	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.12	3.627	0.000	4.6	0.0														
.50	3.908	0.000	19.8	21.0	0.0													
2.18	3.908	0.000	61.9	76.8	75.3	0.0												
3.12	3.906	0.000	64.7	80.8	80.2	37.0	0.0											
5.02	3.903	0.000	70.4	88.9	90.1	86.1	75.0	0.0										
11.12	3.896	0.000	83.7	103.5	108.7	105.4	97.1	76.7	0.0									
17.22	3.887	0.000	91.1	111.5	114.5	115.1	108.0	97.7	80.3	0.0								
23.32	3.886	0.000	96.9	117.8	120.7	122.1	115.6	103.1	96.1	82.9	0.0							
30.02	3.886	0.000	101.8	122.8	126.2	127.8	121.9	117.2	108.0	103.8	64.0	0.0						
38.52	3.886	0.000	106.1	127.3	131.0	133.1	127.2	123.8	116.6	114.9	80.8	56.9	0.0					
47.62	3.886	0.000	110.0	131.7	134.4	136.2	130.9	128.3	122.1	122.2	90.8	70.8	57.5	0.0				
56.72	3.883	0.000	113.4	135.4	137.0	139.0	133.7	131.0	125.0	128.1	97.6	78.4	72.6	56.9	0.0			
65.82	3.870	0.000	115.9	137.9	139.7	141.9	137.0	135.1	130.1	132.4	106.5	91.6	88.1	78.0	74.0	0.0		
74.92	3.858	0.000	117.5	139.2	141.0	143.3	138.3	137.6	133.9	131.6	111.8	97.0	94.1	90.3	87.1	76.1	0.0	
83.42	3.850	0.000	107.2	127.9	132.3	139.1	136.0	132.2	127.8	120.0	107.4	93.8	87.6	94.9	92.7	85.4	46.9	0.0
90.00	-3.949	0.000	43.8	80.2	87.9	98.1	97.7	108.5	109.1	104.4	95.7	83.3	79.0	97.0	99.9	95.3	78.2	88.5
100.00	-1.817	0.000	24.6	61.7	65.6	72.6	71.0	79.3	81.7	79.5	74.1	73.4	68.6	90.3	106.7	107.8	105.2	118.1
110.00	-.691	0.000	16.1	52.1	56.2	61.2	58.8	65.5	66.7	66.7	59.6	54.9	58.6	69.3	80.8	82.8	75.3	84.5
120.00	-.327	0.000	10.4	48.1	51.2	55.6	52.4	57.3	58.4	59.4	48.9	40.5	46.3	52.9	66.2	62.3	54.3	72.4
130.00	-.164	0.000	2.8	44.9	47.6	51.9	48.6	51.6	52.0	50.9	43.2	32.6	38.2	49.0	58.3	58.6	49.9	71.5
140.00	-.058	0.000	0.0	40.0	42.7	46.1	42.2	44.8	45.1	44.6	36.5	28.5	30.4	43.3	56.2	53.9	45.8	64.0
150.00	-.012	0.000	0.0	34.8	37.8	40.6	36.5	39.0	37.9	38.1	29.0	16.8	11.8	30.3	42.8	44.7	36.8	47.4
160.00	-.006	0.000	0.0	29.9	32.9	35.6	31.3	33.4	31.0	32.2	18.4	2.3	0.0	12.8	27.3	26.7	17.3	25.8
170.00	-.005	0.000	0.0	25.1	28.0	31.6	27.9	28.3	24.8	26.2	6.0	0.0	0.0	0.0	9.3	14.0	2.8	16.9
180.00	-.004	0.000	0.0	19.1	22.3	27.1	23.0	21.5	18.7	14.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.9
190.00	-.004	0.000	0.0	12.8	17.2	22.1	17.4	13.3	11.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200.00	-.004	0.000	0.0	6.6	12.4	16.7	9.8	6.4	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
208.80	0.000	0.000	0.0	.9	7.8	11.0	3.4	.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 53.98 MM M2/M/M
DRAINBACK VOLUME = 9.50 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.881 L/S
INFLOW TIME = 83.37 MIN
AVE. SLOPE = .00000 M/M
AVE. TOP WIDTH A = 18.228
AVE. TOP WIDTH B = .683
AVE. WET PERIM A = 18.117
AVE. WET PERIM B = .638
AVE. SHAPE PROF = .403
AVE. SHAPE DEPTH = .284
AVE. SHAPE ADVAN = .682 ^Z

Table 8. Water surface profile data for Test Number 107, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 107

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	18	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		17.02	23.43	14.35	14.69	9.80	0.00	6.73	8.82
*****TOP WIDTH*******									
	R^2	.980	.956	.980	.969	.974	.948	.993	.990
*TW=A(D)^B *	A	25.782	52.246	38.970	23.276	34.982	24.692	11.508	21.570
TW & D, MM	B	.618	.465	.525	.623	.544	.610	.778	.656
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	25.736	52.042	38.754	23.198	34.786	24.572	11.604	21.496
WP & D, MM	B	.628	.473	.535	.636	.554	.624	.794	.669
SURF. SHAPE FACT.									
*PROFILE	*	.302	.219	.224	.299	.475	.291	.595	.381
*DEPTH	*	.248	.180	.184	.246	.390	.242	.329	.183
*ADVANCE	*	.822	.822	.822	.822	.822	.832	.553	.736

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.45	.455	0.000	52.1	0.0						
.57	1.034	0.000	54.0	3.2	0.0					
1.33	1.924	0.000	66.0	23.2	21.2	0.0				
2.18	3.485	0.000	79.3	45.5	44.3	36.4	0.0			
6.85	3.955	0.000	103.0	90.4	93.3	87.9	78.3	0.0		
11.15	3.979	0.000	110.2	98.9	101.9	100.0	94.9	82.0	0.0	
18.75	3.839	0.000	106.4	103.1	104.9	107.9	105.2	104.4	89.3	0.0
20.00	-2.188	0.000	85.2	84.7	91.8	95.9	95.5	101.6	90.8	67.4
30.00	-1.134	0.000	40.3	43.8	50.1	57.0	58.9	73.1	72.7	70.4
40.00	-.331	0.000	30.6	32.7	38.4	44.1	45.5	58.7	57.6	54.6
50.00	-.126	0.000	23.1	24.4	30.0	34.8	35.7	48.5	48.4	45.7
60.00	-.042	0.000	17.6	16.9	22.4	26.9	27.5	39.6	38.5	35.1
70.00	-.012	0.000	14.9	6.3	13.4	14.3	18.3	30.7	29.6	23.4
80.00	-.006	0.000	13.9	0.0	5.5	3.4	10.9	24.0	22.8	13.6
90.00	-.003	0.000	12.0	0.0	0.0	1.2	3.1	14.7	13.4	3.1
100.00	-.001	0.000	11.6	0.0	0.0	0.0	0.0	3.3	4.0	0.0
108.60	0.000	0.000	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 34.21 MM M2/M/M
DRAINBACK VOLUME = 9.50 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.767 L/S
INFLOW TIME = 18.45 MIN
AVE. SLOPE = -.00011 M/M
AVE. TOP WIDTH A = 27.277
AVE. TOP WIDTH B = .598
AVE. WET PERIM A = 27.074
AVE. WET PERIM B = .611
AVE. SHAPE PROF = .343
AVE. SHAPE DEPTH = .250
AVE. SHAPE ADVAN = .789

Table 9. Water surface profile data for Test Number 108, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 108

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	23	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM		44.42	33.81	29.21	37.51	36.32	67.29	76.25	20.27	21.00	10.29	30.04	0.00
*****TOP WIDTH*******													
	R^2	.953	.976	.988	.964	.989	.970	.943	.993	.995	.994	.989	.994
*TW=A(D)^B *	A	48.634	31.664	18.492	34.790	27.774	9.492	51.584	16.768	14.688	13.278	21.902	15.480
TW & D, MM	B	.519	.574	.685	.557	.582	.787	.454	.704	.710	.744	.643	.710
*****WETTED PER******													
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	48.494	31.502	18.482	34.640	27.610	9.636	51.298	16.766	14.692	13.320	21.828	15.496
WP & D, MM	B	.525	.585	.698	.567	.595	.806	.463	.717	.727	.760	.656	.725
SURF. SHAPE FACT.													
*PROFILE	*	.631	.612	.983	.631	.702	.304	.153	.470	.245	.256	.691	.349
*DEPTH	*	.294	.286	.459	.295	.327	.225	.171	.359	.233	.245	.412	.234
*ADVANCE	*	.467	.467	.467	.467	.467	.741	1.113	.764	.950	.957	.596	.673

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM										
0.00	0.000	0.000	0.0										
.08	3.411	0.000	3.6	0.0									
.33	3.831	0.000	15.8	19.6	0.0								
1.48	3.835	0.000	51.9	68.9	49.6	0.0							
3.52	3.854	0.000	67.7	87.5	80.5	61.1	0.0						
9.62	3.904	0.000	94.8	123.5	129.9	113.0	101.4	0.0					
16.62	3.950	0.000	112.6	141.1	147.3	133.3	123.2	86.6	0.0				
21.52	3.966	0.000	119.9	148.8	154.9	141.0	131.4	96.1	51.9	0.0			
28.82	3.982	0.000	126.6	155.2	162.3	148.4	138.8	103.7	64.9	102.7	0.0		
34.92	4.000	0.000	129.3	157.3	159.5	148.0	143.2	106.6	72.4	116.4	77.7	0.0		
41.02	4.017	0.000	131.9	156.6	142.7	136.1	144.4	109.9	77.7	122.2	94.4	78.0	0.0	
51.32	4.040	0.000	131.1	140.1	108.7	106.3	143.4	114.4	83.0	128.9	110.3	103.1	61.0	0.0
60.00	-3.400	0.000	38.9	56.9	66.5	65.2	72.5	55.2	52.6	107.5	104.2	106.9	78.2	98.7
70.00	-.671	0.000	9.4	39.1	42.8	38.3	47.7	30.5	37.2	92.6	91.1	99.0	72.0	92.1
80.00	-.150	0.000	0.0	30.8	33.0	26.3	37.2	18.0	28.6	84.2	82.7	89.6	63.2	84.7
90.00	-.048	0.000	0.0	22.9	25.0	18.8	29.4	6.2	19.9	74.9	73.5	80.9	56.5	73.6
100.00	-.025	0.000	0.0	15.7	16.4	12.7	22.9	0.0	13.0	68.7	66.4	73.0	47.8	65.5
110.00	-.015	0.000	0.0	8.3	9.0	6.4	14.4	0.0	2.7	59.8	56.6	64.4	35.9	55.2
120.00	-.009	0.000	0.0	0.0	2.0	0.0	5.3	0.0	0.0	52.4	50.1	58.5	27.0	45.0
130.00	-.008	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.4	43.5	50.0	20.2	37.4
140.00	-.008	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.7	32.3	38.1	9.7	24.7
150.00	-.006	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.2	24.2	27.7	0.0	11.0
155.40	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.9	22.0	23.0	0.0	5.6

INFLOW VOLUME = 50.49 MM M2/M/M
DRAINBACK VOLUME = 9.88 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.975 L/S
INFLOW TIME = 51.62 MIN
AVE. SLOPE = -.00013 M/M
AVE. TOP WIDTH A = 23.312
AVE. TOP WIDTH B = .630
AVE. WET PERIM A = 23.120
AVE. WET PERIM B = .644
AVE. SHAPE PROF = .516
AVE. SHAPE DEPTH = .295
AVE. SHAPE ADVAN = .605

Table 10. Water surface profile data for Test Number 109, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 109

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	30	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	32.19	19.33	9.97	0.00	1.28	16.39	16.50	30.15	27.50	32.38	22.22	24.09	14.74	8.34	17.47	7.59
*****TOP WIDTH*******																
R^2	.985	.981	.983	.979	.984	.976	.973	.955	.976	.988	.972	.988	.982	.996	.991	.993
*TW=A(D)^B * A	66.562	34.150	20.194	15.162	23.048	12.194	21.430	37.070	9.134	10.278	14.452	11.462	19.458	11.154	11.090	11.856
TW & D, MM B	.431	.566	.664	.727	.641	.774	.645	.554	.827	.807	.721	.765	.658	.781	.770	.754
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	66.386	33.966	20.112	15.180	22.954	12.286	21.340	36.874	9.306	10.424	14.478	11.552	19.374	11.266	11.188	11.948
WP & D, MM B	.436	.576	.678	.741	.653	.788	.659	.563	.842	.821	.737	.782	.673	.796	.787	.771
SURF. SHAPE FACT.																
*PROFILE *	.190	.175	.673	.182	.155	.224	.319	.354	.455	.532	.634	.483	.774	.278	1.000	0.000
*DEPTH *	.184	.170	.653	.177	.151	.204	.236	.261	.281	.481	.421	.274	.556	.213	.645	.646
*ADVANCE *	.971	.971	.971	.971	.971	.912	.739	.736	.617	.904	.663	.568	.718	.768	.450	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.59	3.777	0.000	37.2	0.0														
.92	3.831	0.000	52.1	56.7	0.0													
2.46	3.831	0.000	60.9	68.4	35.2	0.0												
3.73	3.831	0.000	68.2	78.0	61.7	67.5	0.0											
8.22	3.831	0.000	79.2	96.7	101.7	96.8	86.7	0.0										
12.82	3.831	0.000	85.3	104.7	107.6	107.5	99.0	82.1	0.0									
18.92	3.831	0.000	92.0	112.0	115.6	115.6	108.4	99.5	80.6	0.0								
25.62	3.831	0.000	97.6	117.7	121.5	122.3	116.8	110.2	96.2	68.7	0.0							
34.42	3.831	0.000	101.8	123.3	127.0	128.1	122.4	119.3	107.5	86.3	65.4	0.0						
40.82	3.831	0.000	105.7	126.6	131.0	132.3	126.7	124.2	114.2	95.1	79.2	52.8	0.0					
49.92	3.831	0.000	110.6	131.4	136.8	136.8	131.2	130.0	121.4	104.1	91.2	71.0	60.8	0.0				
61.42	3.831	0.000	113.3	134.2	138.4	140.4	135.1	134.3	126.6	109.7	98.8	80.6	77.7	58.2	0.0			
71.12	3.831	0.000	115.6	136.8	141.3	143.5	138.7	137.9	130.3	114.2	105.5	88.2	87.3	74.0	72.4	0.0		
80.52	3.831	0.000	118.7	139.8	144.2	146.6	141.4	141.1	133.6	118.1	108.6	94.1	94.8	84.7	86.7	67.3	0.0	
94.12	3.742	0.000	110.0	122.6	123.4	145.2	142.4	139.7	133.9	121.1	111.9	97.8	100.0	92.4	96.7	88.9	68.0	0.0
100.00	-4.438	0.000	63.1	85.4	93.7	101.4	101.1	112.6	111.2	103.8	102.0	93.8	97.7	92.0	100.5	95.0	79.7	73.8
110.00	-1.656	0.000	51.7	64.3	71.1	79.9	78.3	86.0	85.6	77.9	76.2	70.1	80.7	81.4	96.2	96.3	87.4	99.6
120.00	-.678	0.000	43.0	57.0	63.3	69.0	66.8	75.0	73.4	65.6	64.2	59.4	69.5	70.2	87.1	87.9	79.7	91.1
130.00	-.313	0.000	33.9	51.6	57.1	61.8	58.7	64.4	62.3	54.4	52.3	46.7	56.8	57.4	72.1	74.8	64.5	74.4
140.00	-.144	0.000	27.5	46.8	51.9	55.9	52.4	56.8	53.9	45.0	42.3	36.2	46.4	46.9	61.8	64.0	53.1	63.2
150.00	-.049	0.000	20.7	42.1	47.1	50.6	46.7	50.7	47.4	38.5	35.6	29.3	38.4	38.5	53.8	54.9	45.2	56.9
160.00	-.006	0.000	1.4	36.8	42.0	45.2	41.1	44.6	40.7	30.8	27.4	15.6	24.1	25.2	40.6	43.6	33.6	38.9
170.00	0.000	0.000	0.0	31.6	36.8	40.2	36.4	38.8	35.6	26.0	21.5	5.3	13.5	13.4	31.8	31.2	22.6	31.1
180.00	0.000	0.000	0.0	26.6	31.7	35.3	31.5	32.3	28.4	17.2	7.9	0.0	0.0	0.0	14.2	13.1	3.1	15.8
190.00	0.000	0.000	0.0	20.4	26.0	30.1	26.9	25.5	21.6	10.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200.00	0.000	0.000	0.0	14.9	20.0	25.8	21.7	18.3	13.4	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
210.00	0.000	0.000	0.0	8.2	14.4	19.2	14.4	10.7	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
220.00	0.000	0.000	0.0	2.3	9.8	13.9	6.4	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
223.20	0.000	0.000	0.0	1.8	9.5	13.5	5.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 59.94 MM M2/M/M
DRAINBACK VOLUME = 9.11 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.831 L/S
INFLOW TIME = 93.80 MIN
AVE. SLOPE = .00000 M/M
AVE. TOP WIDTH A = 18.228
AVE. TOP WIDTH B = .683
AVE. WET PERIM A = 18.117
AVE. WET PERIM B = .698
AVE. SHAPE PROF = .429
AVE. SHAPE DEPTH = .347
AVE. SHAPE ADVAN = .818 ^Z

Table 11. Water surface profile data for Test Number 110, Table 1.

```
MAC FURROW DRAINBACK STUDY NUMBER 110
   NO. STA      NO. TIME PERIODS    FURROW SPACING
     8               14                  1.016
                   STA 1   STA 2   STA 3   STA 4   STA 5   STA 6   STA 7   STA 8
      DISTANCE, M   0.0     5.0    10.0    20.0    30.0    60.0    90.0   120.0
    ELEVATIONS, MM  0.00    4.42    7.59   11.69    9.31   10.31   11.38    5.82
*****TOP WIDTH*******
               R^2  .945    .980    .985    .980    .972    .965    .966    .991
   *TW=A(D)^B * A  59.156  30.018  19.752  26.298  32.658  32.436  11.586  16.970
   *TW & D, MM* B   .461    .598    .671    .604    .570    .563    .766    .703
*****WETTED PER******
               R^2 1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000
   *WP=A(D)^B * A  58.896  29.942  19.714  26.172  32.492  32.314  11.680  16.962
   *WP & D, MM* B   .468    .606    .683    .616    .581    .574    .782    .717
**SURF. SHAPE FACT.**
   *PROFILE   *     .870    .365    .437    .834    .593    .314    .279    .354
   *DEPTH     *     .379    .159    .190    .363    .258    .230    .178    .328
   *ADVANCE   *     .436    .436    .436    .436    .436    .732    .637    .736

  TIME  Q IN Q OUT  HEAD
   MIN  L/S   L/S    MM

  0.00 0.000 0.000   0.0
   .08 3.397 0.000   3.7     0.0
   .29 3.776 0.000  12.9     5.7     0.0
  1.44 3.777 0.000  63.4    37.1    31.8     0.0
  3.65 3.785 0.000 106.2    84.0    77.8    56.8     0.0
 10.68 3.810 0.000 117.6    99.9    95.7    88.9    82.6     0.0
 18.58 3.831 0.000 125.2   109.0   105.3   100.7    96.7    81.3     0.0
 29.18 3.831 0.000 136.5   119.2   115.4   111.5   108.4    96.7    79.2     0.0
 30.00 3.831 0.000 129.0   117.2   114.0   111.0   107.2    97.2    80.5    46.3
 40.00-1.456 0.000  47.2    43.4    43.4    48.0    50.5    55.1    59.0    63.5
 50.00 -.246 0.000  33.4    26.0    24.0    28.1    29.2    31.2    34.7    39.7
 60.00 -.029 0.000  21.1    11.0     9.4    11.6    12.9    11.6    17.1    16.6
 70.00 -.012 0.000   4.9     0.0     0.0      .1     0.0     0.0     4.1     0.0
 75.00 -.009 0.000   0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0

     INFLOW VOLUME     =    57.48 MM M2/M/M
     DRAINBACK VOLUME  =     9.75 MM M2/M/M
     RUNOFF VOLUME     =     0.00 MM M2/M/M
     AVE. INFLOW RATE  =    3.819 L/S
     INFLOW TIME       =    30.58 MIN
     AVE. SLOPE        =   .00003  M/M
     AVE. TOP WIDTH A  =   26.692
     AVE. TOP WIDTH B  =     .610
     AVE. WET PERIM A  =   26.493
     AVE. WET PERIM B  =     .622
     AVE. SHAPE PROF   =     .527
     AVE. SHAPE DEPTH  =     .261
     AVE. SHAPE ADVAN  =     .531
```

Table 12. Water surface profile data for Test Number 111, Talble 1.

MAC FURROW DRAINBACK STUDY NUMBER 111

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	18	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM		35.53	22.43	32.83	26.39	13.70	21.71	22.50	25.44	20.00	13.46	10.46	0.00
*****TOP WIDTH*******													
	R^2	.964	.989	.962	.960	.987	.983	.971	.975	.981	.969	.987	.979
*TW=A(D)^B *	A	45.932	42.008	42.602	67.380	23.140	29.370	25.448	15.220	16.856	34.590	21.090	12.560
TW & D, MM	B	.513	.516	.501	.413	.627	.590	.610	.714	.699	.536	.642	.762
*****WETTED PER******													
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	45.776	41.744	42.366	67.016	23.044	29.242	25.304	15.240	16.856	34.356	21.002	12.642
WP & D, MM	B	.520	.526	.511	.420	.640	.600	.623	.729	.713	.548	.657	.777
SURF. SHAPE FACT.													
*PROFILE	*	.416	.336	.443	.555	.268	.592	.266	.417	.464	.551	.271	.483
*DEPTH	*	.170	.137	.181	.227	.109	.310	.190	.271	.279	.294	.157	.220
*ADVANCE	*	.408	.408	.408	.408	.408	.523	.715	.649	.601	.534	.581	.568

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM										
0.00	0.000	0.000	0.0										
.07	3.342	0.000	1.5	0.0									
.36	3.831	0.000	8.2	10.7	0.0								
1.94	3.831	0.000	44.6	58.6	44.9	0.0							
5.24	3.838	0.000	71.4	94.4	76.8	72.6	0.0						
9.30	3.856	0.000	78.7	103.0	86.6	89.0	91.5	0.0					
20.20	3.894	0.000	89.4	114.1	98.8	103.6	109.0	83.8	0.0				
30.20	3.930	0.000	95.2	119.7	105.0	110.5	116.7	96.1	80.0	0.0			
42.60	3.895	0.000	99.5	123.3	108.6	115.3	122.2	104.9	92.5	73.2	0.0		
57.70	3.845	0.000	103.7	128.5	113.6	120.6	128.3	112.2	102.1	88.1	71.3	0.0		
77.00	3.793	0.000	107.8	132.0	117.5	124.4	132.2	117.0	107.7	95.9	85.1	74.7	0.0	
96.90	3.776	0.000	108.8	133.6	119.2	127.1	134.3	121.3	113.7	103.3	95.2	91.4	65.7	0.0
100.00	-.027	0.000	73.7	102.8	96.0	108.2	118.0	112.3	109.4	102.7	94.9	94.7	69.9	62.8
110.00	-2.407	0.000	17.0	48.9	40.0	56.5	69.5	67.9	69.0	68.6	71.6	77.0	69.8	81.6
120.00	-.408	0.000	4.8	36.7	24.7	39.0	50.2	46.3	47.0	46.5	48.1	55.2	49.1	61.3
130.00	-.081	0.000	0.0	23.2	10.0	22.6	32.8	26.5	25.8	24.2	27.0	32.9	23.6	34.5
140.00	-.017	0.000	0.0	4.7	0.0	7.0	17.1	4.9	7.3	2.1	7.6	7.4	.7	9.0
147.60	0.000	0.000	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 92.97 MM M2/M/M
DRAINBACK VOLUME = 8.59 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.840 L/S
INFLOW TIME = 98.40 MIN
AVE. SLOPE = -.00009 M/M
AVE. TOP WIDTH A = 28.806
AVE. TOP WIDTH B = .587
AVE. WET PERIM A = 28.547
AVE. WET PERIM B = .600
AVE. SHAPE PROF = .416
AVE. SHAPE DEPTH = .212
AVE. SHAPE ADVAN = .552

Table 13. Water surface profile data for Test Number 112, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 112

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	24	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	16.33	7.72	17.36	18.14	21.17	18.28	15.94	14.61	6.44	2.03	9.83	1.29	2.97	5.23	8.14	0.00
*****TOP WIDTH*******																
R^2	.971	.976	.988	.930	.956	.952	.989	.945	.978	.934	.981	.955	.960	.977	.953	.998
*TW=A(D)^B * A	85.324	42.528	38.558	43.012	33.696	24.366	23.886	16.850	33.539	19.070	31.508	23.182	44.474	37.342	30.516	6.392
TW & D, MM B	.373	.518	.545	.514	.568	.653	.633	.701	.569	.682	.594	.646	.498	.553	.581	.872
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	85.048	42.310	38.364	42.746	33.498	24.320	23.782	16.832	33.329	19.018	31.392	23.076	44.216	37.114	30.350	6.672
WP & D, MM B	.378	.527	.554	.524	.578	.663	.646	.716	.580	.696	.603	.658	.507	.563	.593	.890
SURF. SHAPE FACT.																
*PROFILE *	.196	.138	.262	.175	.179	.249	.249	.324	.138	.379	.551	.941	.548	.558	.268	0.000
*DEPTH *	.202	.143	.270	.180	.185	.197	.194	.196	.166	.230	.357	.426	.277	.264	.219	.505
*ADVANCE *	1.030	1.030	1.030	1.030	1.030	.790	.778	.605	.839	.607	.648	.453	.505	.473	.818	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
1.18	3.913	0.000	36.8	0.0														
2.31	3.941	0.000	71.4	76.6	0.0													
4.52	3.941	0.000	80.7	88.0	56.8	0.0												
6.70	3.941	0.000	89.8	97.1	82.3	64.2	0.0											
11.78	3.941	0.000	93.9	107.6	98.1	83.5	71.7	0.0										
19.68	3.941	0.000	108.6	116.7	107.8	95.3	86.7	84.2	0.0									
28.48	3.941	0.000	115.5	123.7	114.9	103.2	95.8	93.6	78.5	0.0								
41.18	3.941	0.000	122.0	131.9	121.4	110.4	103.7	110.3	94.0	81.8	0.0							
51.18	3.941	0.000	124.5	134.8	124.6	113.4	106.7	114.6	100.2	92.8	80.8	0.0						
65.98	3.941	0.000	128.4	138.3	128.0	117.1	110.8	119.8	106.4	101.7	96.1	82.8	0.0					
81.08	3.941	0.000	130.1	139.4	130.5	119.6	113.2	122.9	110.1	106.9	103.0	96.8	70.6	0.0				
105.18	3.941	0.000	131.8	139.9	130.8	121.0	115.2	125.9	114.3	111.4	110.2	103.8	85.0	81.0	0.0			
129.58	3.941	0.000	133.8	142.2	133.2	123.6	118.0	128.7	117.8	115.7	115.8	111.0	94.3	95.4	78.8	0.0		
158.48	3.941	0.000	136.9	145.1	136.2	126.5	120.8	131.8	121.3	119.7	120.1	115.8	93.9	102.4	86.9	65.6	0.0	
172.68	3.941	0.000	123.6	148.7	139.3	131.3	117.4	134.2	121.2	121.3	122.8	119.0	104.2	106.9	93.4	73.7	49.9	0.0
180.00	-3.762	0.000	50.4	65.7	64.7	68.6	71.7	97.0	94.6	102.4	109.3	110.7	98.6	103.3	92.1	75.0	54.4	57.0
190.00	-1.549	0.000	30.4	48.1	46.3	45.6	45.7	69.3	67.3	73.0	81.5	83.9	75.9	85.1	78.9	68.6	60.7	70.0
200.00	-.468	0.000	21.6	38.0	37.1	33.9	32.7	53.1	49.9	54.9	62.5	64.9	55.9	64.9	59.3	49.7	45.7	56.6
210.00	-.140	0.000	12.9	30.0	29.7	23.6	20.3	37.7	33.2	37.6	42.7	43.6	35.4	44.8	37.8	24.1	13.8	25.4
220.00	-.023	0.000	2.5	23.1	24.1	15.7	8.7	24.2	17.5	23.4	23.0	19.6	13.5	21.5	15.9	1.2	0.0	0.0
230.00	-.012	0.000	0.0	15.4	17.7	7.3	0.0	8.2	0.0	8.3	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
240.00	-.008	0.000	0.0	7.5	10.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
248.40	-.005	0.000	0.0	.5	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 113.98 MM M2/M/M
DRAINBACK VOLUME = 8.73 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.941 L/S
INFLOW TIME = 173.38 MIN
AVE. SLOPE = -.00004 M/M
AVE. TOP WIDTH A = 30.593
AVE. TOP WIDTH B = .585
AVE. WET PERIM A = 30.293
AVE. WET PERIM B = .598
AVE. SHAPE PROF = .348
AVE. SHAPE DEPTH = .251
AVE. SHAPE ADVAN = .844 ^Z

Table 14. Water surface profile data for Test Number 113, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 113

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	16	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		0.00	4.42	7.59	11.69	9.31	10.31	11.38	5.82
*****TOP WIDTH*******									
	R^2	.945	.980	.985	.980	.972	.965	.966	.991
*TW=A(D)^B *	A	59.155	30.018	19.752	26.298	32.658	32.496	11.586	16.970
TW & D, MM	B	.461	.598	.671	.604	.570	.563	.766	.703
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	58.896	29.942	19.714	26.172	32.492	32.314	11.680	16.962
WP & D, MM	B	.468	.606	.683	.616	.581	.574	.782	.717
SURF. SHAPE FACT.									
*PROFILE	*	.077	.087	.093	.116	.277	.164	.506	.324
*DEPTH	*	.118	.134	.143	.179	.426	.204	.309	.177
*ADVANCE	*	1.538	1.538	1.538	1.538	1.538	1.242	.611	.605

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM						
0.00	0.000	0.000	0.0						
.76	3.789	0.000	31.9	0.0					
1.20	3.831	0.000	50.1	39.7	0.0				
1.88	3.831	0.000	78.6	62.4	55.1	0.0			
2.44	3.831	0.000	101.9	81.2	71.8	56.3	0.0		
8.03	3.837	0.000	117.1	101.5	96.4	89.2	85.0	0.0	
11.13	3.875	0.000	123.2	108.3	103.9	98.2	94.9	78.9	0.0	
17.83	3.849	0.000	123.2	111.3	108.5	105.7	104.9	96.7	82.6	0.0
20.00	.071	0.000	89.5	84.0	84.4	87.3	90.4	92.3	88.2	81.9
30.00	-1.840	0.000	56.1	50.5	49.1	52.0	56.1	60.6	65.0	69.1
40.00	-.393	0.000	46.5	39.9	37.7	38.8	41.9	45.7	50.6	56.4
50.00	-.135	0.000	41.2	33.4	30.6	30.3	32.6	34.0	38.2	43.1
60.00	-.043	0.000	36.6	27.9	24.7	23.6	25.4	26.2	29.9	34.1
70.00	-.014	0.000	30.3	21.1	18.0	16.4	18.0	18.3	22.3	23.9
80.00	-.008	0.000	22.4	13.8	11.0	8.6	10.1	6.9	11.3	12.6
90.00	0.000	0.000	3.1	5.0	2.8	1.4	1.5	.0	3.3	1.9

INFLOW VOLUME = 35.07 MM M2/M/M
DRAINBACK VOLUME = 13.24 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.845 L/S
INFLOW TIME = 18.53 MIN
AVE. SLOPE = .00003 M/M
AVE. TOP WIDTH A = 26.692
AVE. TOP WIDTH B = .610
AVE. WET PERIM A = 26.493
AVE. WET PERIM B = .622
AVE. SHAPE PROF = .189
AVE. SHAPE DEPTH = .211
AVE. SHAPE ADVAN = .953

Table 15. Water surface profile data for Test Number 114, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 114

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	23	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	35.53	22.43	32.83	26.39	13.70	21.71	22.50	25.44	20.00	13.46	10.46	0.00
*****TOP WIDTH*******												
R^2	.964	.989	.962	.960	.987	.983	.971	.975	.981	.969	.987	.979
*TW=A(D)^B * A	45.932	42.008	42.602	67.380	23.140	29.370	25.448	15.220	16.856	34.590	21.090	12.560
TW & D, MM B	.513	.516	.501	.413	.627	.590	.610	.714	.699	.536	.642	.762
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	45.776	41.744	42.366	67.016	23.044	29.242	25.304	15.240	16.856	34.356	21.002	12.642
WP & D, MM B	.520	.526	.511	.420	.640	.600	.623	.729	.713	.548	.657	.777
SURF. SHAPE FACT.												
*PROFILE *	.813	.069	.077	.106	.183	.263	.309	.352	1.000	.311	.682	.941
*DEPTH *	.372	.032	.035	.049	.084	.178	.228	.220	.715	.260	.359	.144
*ADVANCE *	.458	.458	.458	.458	.458	.678	.739	.626	.591	.837	.527	.453

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.05	3.077	0.000	6.1	0.0										
.21	3.776	0.000	21.5	7.2	0.0									
.93	3.776	0.000	37.1	32.6	26.5	0.0								
3.25	3.758	0.000	71.9	103.2	90.1	94.7	0.0							
6.35	3.717	0.000	75.1	105.2	92.1	98.0	92.0	0.0						
11.55	3.624	0.000	77.9	107.8	94.9	102.1	98.2	74.2	0.0					
17.05	3.426	0.000	80.8	111.8	98.6	107.7	105.0	86.7	69.5	0.0				
24.35	3.215	0.000	86.3	116.4	103.5	113.3	111.2	94.3	81.6	63.4	0.0			
33.15	3.601	0.000	95.1	124.8	112.5	121.7	119.5	103.6	92.6	78.6	63.7	0.0		
39.85	3.997	0.000	100.4	130.3	117.6	127.7	125.7	111.0	101.2	89.5	78.2	67.7	0.0	
51.35	3.858	0.000	88.4	109.4	100.5	110.9	120.9	115.3	107.5	100.9	94.1	89.3	68.4	0.0
60.00	-3.205	0.000	28.2	57.8	47.6	62.6	75.8	76.7	76.0	75.8	78.3	84.3	80.0	93.3
70.00	-.888	0.000	18.2	46.1	35.3	48.7	60.8	64.0	63.1	59.6	61.7	68.0	61.3	75.6
80.00	-.400	0.000	11.6	39.8	28.1	40.8	52.4	55.4	53.0	46.0	48.8	55.4	48.6	63.2
90.00	-.204	0.000	6.2	34.4	21.9	33.4	44.2	45.4	42.5	37.8	39.8	45.2	39.2	53.3
100.00	-.082	0.000	.5	29.0	16.1	26.4	37.0	36.9	33.8	30.0	32.8	40.4	35.4	48.6
110.00	-.026	0.000	0.0	22.7	9.8	20.1	30.5	30.0	26.7	22.0	24.3	30.4	24.4	36.4
120.00	-.013	0.000	0.0	15.2	2.4	13.8	24.3	22.1	17.7	12.7	15.1	19.6	12.2	23.3
130.00	-.011	0.000	0.0	6.8	0.0	7.7	18.2	13.4	10.1	3.6	7.8	7.9	2.5	7.7
140.00	-.007	0.000	0.0	0.0	0.0	1.1	10.6	5.4	3.2	0.0	1.5	2.0	0.0	0.0
150.00	-.005	0.000	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
153.00	-.001	0.000	0.0	0.0	0.0	0.0	.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 46.19 MM M2/M/M
DRAINBACK VOLUME = 10.85 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.684 L/S
INFLOW TIME = 50.95 MIN
AVE. SLOPE = -.00009 M/M
AVE. TOP WIDTH A = 28.806
AVE. TOP WIDTH B = .587
AVE. WET PERIM A = 28.547
AVE. WET PERIM B = .600
AVE. SHAPE PROF = .379
AVE. SHAPE DEPTH = .223
AVE. SHAPE ADVAN = .563

Table 16. Water surface profile data for Test Number 115, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 115

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	29	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	16.33	7.72	17.36	18.14	21.17	18.28	15.94	14.61	6.44	2.03	9.83	1.29	2.97	5.29	8.14	0.00
*****TOP WIDTH*******																
R^2	.971	.976	.988	.930	.956	.952	.989	.945	.978	.984	.981	.955	.960	.977	.963	.998
*TW=A(D)^B * A	85.324	42.528	30.558	43.012	33.636	24.366	23.886	16.850	33.538	19.070	31.508	23.182	44.474	37.342	30.516	6.332
TW & D, MM B	.373	.518	.545	.514	.568	.653	.633	.701	.569	.682	.534	.646	.498	.553	.591	.872
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	85.048	42.310	38.354	42.746	33.498	24.320	23.782	16.832	33.328	19.018	31.382	23.076	44.216	37.114	30.350	6.672
WP & D, MM B	.378	.527	.554	.524	.578	.663	.646	.716	.580	.696	.603	.658	.507	.563	.593	.830
SURF. SHAPE FACT.																
*PROFILE *	.187	.143	.144	.168	.172	.283	.235	.537	.225	.397	.850	.548	.616	.675	.384	0.000
*DEPTH *	.237	.181	.182	.213	.218	.244	.260	.273	.225	.321	.403	.440	.393	.459	.321	.427
*ADVANCE *	1.264	1.264	1.264	1.264	1.264	.863	1.108	.508	1.003	.810	.474	.803	.646	.680	.835	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.38	3.963	0.000	30.4	0.0														
1.70	3.938	0.000	52.6	55.2	0.0													
2.95	4.003	0.000	71.1	77.2	63.2	0.0												
4.06	4.003	0.000	77.1	83.2	70.0	35.0	0.0											
7.17	4.020	0.000	89.3	97.4	86.2	72.2	62.6	0.0										
11.47	4.040	0.000	93.0	107.4	97.3	85.2	77.6	74.1	0.0									
14.87	4.053	0.000	103.9	112.5	102.6	91.5	84.3	86.9	65.3	0.0								
23.07	4.053	0.000	112.3	120.8	111.1	100.8	94.8	102.0	87.1	71.6	0.0							
27.67	4.048	0.000	115.9	124.6	114.8	104.7	98.7	107.5	93.5	84.3	72.0	0.0						
33.47	4.033	0.000	119.4	128.3	118.8	108.7	103.1	112.8	100.4	91.6	86.8	71.0	0.0					
44.36	4.010	0.000	123.1	131.7	122.4	112.3	106.9	116.1	107.6	103.8	99.0	92.0	68.5	0.0				
51.37	3.997	0.000	125.4	133.8	124.6	114.7	109.7	120.9	110.3	107.9	107.9	102.3	82.2	77.4	0.0			
60.47	3.997	0.000	126.8	137.5	126.8	116.4	111.6	123.8	113.2	112.6	113.7	112.3	91.7	96.4	73.8	0.0		
69.57	3.997	0.000	128.7	138.2	128.9	119.7	113.5	126.1	118.6	119.1	120.4	116.6	100.3	105.8	90.5	64.7	0.0	
75.67	3.997	0.000	126.5	133.8	124.5	117.1	116.0	127.4	121.0	120.2	123.4	118.3	105.5	109.5	95.4	78.2	54.7	0.0
80.00	-3.593	0.000	76.5	90.3	86.1	87.5	85.1	111.3	108.8	112.1	120.4	119.2	104.5	109.8	98.9	83.6	69.3	60.4
90.00	-2.625	0.000	40.7	57.8	52.2	50.4	51.6	77.1	77.5	85.0	93.9	94.7	88.4	97.9	96.3	91.2	88.6	99.7
100.00	-1.126	0.000	32.4	48.9	42.4	39.9	39.9	64.2	64.2	71.8	81.9	82.7	76.0	84.8	83.7	84.6	83.6	95.3
110.00	-.583	0.000	29.1	44.6	37.9	34.2	33.9	56.6	54.8	61.5	70.1	72.0	65.8	75.7	70.1	70.5	69.0	79.1
120.00	-.356	0.000	24.3	39.4	32.6	27.5	26.5	47.5	45.4	51.0	60.5	64.3	57.9	66.8	61.0	59.9	56.7	66.1
130.00	-.193	0.000	18.1	35.4	28.2	21.7	19.2	38.2	33.3	43.9	52.7	51.2	48.5	55.7	54.1	50.3	46.4	56.0
140.00	-.093	0.000	14.0	32.3	25.1	17.9	14.7	32.8	29.7	35.1	43.1	45.3	39.0	46.9	46.1	38.1	33.0	43.5
150.00	-.035	0.000	10.0	29.1	21.1	13.3	9.5	26.4	22.0	27.1	33.1	36.2	26.5	34.7	34.9	20.7	14.3	24.0
160.00	-.012	0.000	3.0	25.4	17.3	9.2	3.9	21.0	16.7	21.7	27.6	28.8	19.8	29.9	28.4	10.2	.8	10.3
170.00	-.009	0.000	0.0	22.2	14.7	6.0	0.0	14.4	9.1	16.0	18.5	14.9	11.2	21.0	19.0	0.0	0.0	0.0
180.00	-.007	0.000	0.0	18.3	11.5	1.7	0.0	6.6	.5	9.6	11.2	3.0	1.9	9.0	8.5	0.0	0.0	0.0
190.00	-.005	0.000	0.0	14.2	8.3	0.0	0.0	0.0	0.0	3.7	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
195.00	0.000	0.000	0.0	12.4	6.7	0.0	0.0	0.0	0.0	.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 51.27 MM M2/M/M
DRAINBACK VOLUME = 11.59 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.016 L/S
INFLOW TIME = 76.52 MIN
AVE. SLOPE = -.00004 M/M
AVE. TOP WIDTH A = 30.579
AVE. TOP WIDTH B = .535
AVE. WET PERIM A = 30.293
AVE. WET PERIM B = .598
AVE. SHAPE PROF = .371
AVE. SHAPE DEPTH = .300
AVE. SHAPE ADVAN = .947

Table 17. Water surface profile data for Test Number 116, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 116

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	17	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		0.00	4.42	7.59	11.69	9.31	10.31	11.38	5.82
*****TOP WIDTH*******									
	R^2	.945	.980	.985	.980	.972	.965	.966	.991
*TW=A(D)^B *	A	59.156	30.018	19.752	26.298	32.658	32.496	11.586	16.970
TW & D, MM	B	.461	.598	.671	.604	.570	.563	.766	.703
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	58.896	29.942	19.714	26.172	32.492	32.314	11.680	16.962
WP & D, MM	B	.468	.606	.683	.616	.581	.574	.782	.717
SURF. SHAPE FACT.									
*PROFILE *		.203	.290	.332	.495	.491	.315	.914	.537
*DEPTH *		.116	.166	.189	.282	.280	.279	.467	.145
*ADVANCE *		.570	.570	.570	.570	.570	.885	.511	.508

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.06	3.292	0.000	4.7	0.0						
.20	3.831	0.000	15.9	11.2	0.0					
.67	3.831	0.000	53.6	37.8	32.0	0.0				
1.85	3.831	0.000	95.6	74.0	67.6	50.6	0.0			
5.85	3.863	0.000	110.8	91.4	86.8	79.5	70.8	0.0		
9.25	3.846	0.000	116.6	98.3	94.4	88.8	84.2	65.7	0.0	
16.25	3.880	0.000	111.4	94.7	92.9	92.6	92.7	88.4	74.1	0.0
20.00	-2.669	0.000	65.4	56.7	55.1	59.3	60.1	65.5	72.0	75.3
30.00	-.805	0.000	50.3	39.4	37.6	39.7	41.3	45.6	50.7	55.5
40.00	-.240	0.000	41.5	29.5	27.1	27.7	28.4	31.7	36.0	40.2
50.00	-.081	0.000	35.3	23.6	21.0	20.5	20.4	20.4	22.3	24.6
60.00	-.023	0.000	26.3	17.1	14.5	12.4	12.3	11.1	13.9	13.1
70.00	-.010	0.000	19.7	11.2	8.6	6.1	5.3	2.3	6.5	6.4
80.00	-.015	0.000	10.1	4.2	1.7	.4	0.0	0.0	1.7	.6
90.00	-.004	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
91.20	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME =	30.88 MM M2/M/M
DRAINBACK VOLUME =	10.72 MM M2/M/M
RUNOFF VOLUME =	0.00 MM M2/M/M
AVE. INFLOW RATE =	3.861 L/S
INFLOW TIME =	16.25 MIN
AVE. SLOPE =	.00003 M/M
AVE. TOP WIDTH A =	26.692
AVE. TOP WIDTH B =	.610
AVE. WET PERIM A =	26.493
AVE. WET PERIM B =	.622
AVE. SHAPE PROF =	.434
AVE. SHAPE DEPTH =	.240
AVE. SHAPE ADVAN =	.559

Table 18. Water surface profile data for Test Number 117, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 117

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	22	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	35.53	22.43	32.83	26.39	13.70	21.71	22.50	25.44	20.00	13.46	10.46	0.00
*****TOP WIDTH*******												
R^2	.954	.989	.962	.960	.987	.983	.971	.975	.981	.969	.987	.979
*TW=A(D)^B * A	45.932	42.008	42.602	67.380	23.140	29.370	25.448	15.220	16.856	34.590	21.090	12.560
TW & D, MM B	.513	.516	.501	.413	.627	.590	.610	.714	.699	.536	.642	.762
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	45.776	41.744	42.366	67.016	23.044	29.242	25.304	15.240	16.856	34.356	21.002	12.642
WP & D, MM B	.520	.526	.511	.420	.640	.600	.623	.729	.713	.548	.657	.777
SURF. SHAPE FACT.												
*PROFILE *	.333	.316	.198	.238	.235	.408	.435	.846	.407	.329	.166	.548
*DEPTH *	.315	.299	.187	.225	.222	.274	.368	.555	.242	.216	.117	.205
*ADVANCE *	.945	.945	.945	.945	.945	.673	.845	.656	.594	.657	.703	.803

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.45	3.291	0.000	26.1	0.0										
.93	3.353	0.000	34.6	35.3	0.0									
1.94	3.351	0.000	45.7	53.0	25.0	0.0								
2.98	3.345	0.000	55.4	71.3	46.3	41.9	0.0							
7.02	3.329	0.000	66.3	88.8	70.0	72.7	76.0	0.0						
12.82	3.299	0.000	75.0	97.2	80.5	86.0	92.2	69.0	0.0					
18.02	3.265	0.000	80.7	103.0	87.0	93.8	100.6	82.9	61.8	0.0				
25.32	3.251	0.000	86.1	109.0	93.5	100.3	108.4	93.3	79.4	60.6	0.0			
34.42	3.251	0.000	89.4	112.3	98.7	110.4	113.5	99.2	88.0	75.6	56.8	0.0		
43.52	3.251	0.000	92.9	116.1	104.2	113.5	117.2	104.5	94.2	85.2	74.5	62.9	0.0	
52.62	3.251	0.000	95.8	118.8	107.1	116.8	121.0	109.8	100.8	91.7	81.1	76.6	53.4	0.0
60.00	.496	0.000	44.5	81.3	74.7	91.3	99.7	96.6	94.5	88.9	84.5	83.4	65.9	78.1
70.00	-1.636	0.000	20.6	49.9	41.7	57.7	65.8	63.8	66.5	67.4	71.4	77.8	75.2	88.2
80.00	-.527	0.000	13.4	41.0	32.0	46.6	54.0	51.4	53.5	53.9	56.7	62.4	59.5	72.4
90.00	-.222	0.000	8.6	35.2	25.3	38.1	44.9	41.0	42.0	40.8	40.9	47.0	41.2	53.0
100.00	-.101	0.000	3.8	30.3	19.5	31.9	38.6	33.7	34.4	33.6	35.0	40.6	33.5	42.7
110.00	-.029	0.000	0.0	24.1	12.4	24.6	30.9	24.3	24.3	22.4	24.5	30.6	22.0	34.2
120.00	-.015	0.000	0.0	16.1	4.4	18.0	24.4	15.6	14.5	13.3	17.1	20.6	9.8	23.7
130.00	-.010	0.000	0.0	4.6	0.0	10.2	16.3	5.6	5.3	1.6	5.7	6.4	0.0	3.9
140.00	-.007	0.000	0.0	0.0	0.0	4.1	9.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
145.20	0.000	0.000	0.0	0.0	0.0	1.7	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 45.72 MM M2/M/M
DRAINBACK VOLUME = 8.77 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.267 L/S
INFLOW TIME = 56.87 MIN
AVE. SLOPE = -.00009 M/M
AVE. TOP WIDTH A = 28.806
AVE. TOP WIDTH B = .587
AVE. WET PERIM A = 28.547
AVE. WET PERIM B = .600
AVE. SHAPE PROF = .356
AVE. SHAPE DEPTH = .269
AVE. SHAPE ADVAN = .802

Table 19. Water surface profile data for Test Number 118, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 118

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	27	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM		16.33	7.72	17.36	18.14	21.17	18.28	15.94	14.61	6.44	2.03	9.89	1.29	2.97	5.23	8.14	0.00
*****TOP WIDTH*******																	
	R^2	.971	.976	.988	.930	.956	.952	.989	.945	.978	.934	.981	.955	.960	.977	.963	.938
*TW=A(D)^B *	A	85.324	42.528	38.559	43.012	33.695	24.366	23.886	16.850	33.539	19.070	31.503	23.183	44.474	37.342	30.516	6.332
TW & D, MM	B	.373	.518	.545	.514	.568	.653	.633	.701	.559	.682	.534	.646	.498	.553	.581	.872
*****WETTED PER******																	
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	85.048	42.310	38.354	42.746	33.438	24.320	23.782	16.832	33.328	19.018	31.392	23.076	44.216	37.114	30.350	6.672
WP & D, MM	B	.378	.527	.554	.524	.578	.663	.646	.716	.580	.696	.603	.658	.507	.563	.593	.890
SURF. SHAPE FACT.																	
*PROFILE	*	.278	.251	.340	.249	.379	.173	.526	.315	.427	.533	.677	.515	.739	.189	.340	0.000
*DEPTH	*	.179	.162	.219	.160	.244	.249	.315	.218	.319	.481	.336	.318	.375	.137	.648	.687
*ADVANCE	*	.644	.644	.644	.544	.644	1.330	.538	.690	.748	.759	.585	.619	.508	.723	.689	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.37	3.638	0.000	50.0	0.0														
1.08	3.722	0.000	54.9	45.6	0.0													
3.16	3.723	0.000	69.4	72.6	60.8	0.0												
3.26	3.729	0.000	70.1	73.9	63.1	46.0	0.0											
7.38	3.748	0.000	88.4	96.2	86.5	72.9	61.7	0.0										
9.88	3.778	0.000	94.0	102.0	91.8	73.0	70.0	61.8	0.0									
15.98	3.814	0.000	102.4	111.1	101.0	89.8	82.4	84.3	62.2	0.0								
22.08	3.803	0.000	107.5	116.4	106.8	96.4	89.5	95.6	79.0	64.6	0.0							
28.18	3.768	0.000	111.2	120.2	111.0	100.5	94.1	101.6	88.4	77.3	62.1	0.0						
34.53	3.739	0.009	114.0	123.2	114.5	103.4	97.1	105.7	94.1	87.1	80.3	55.5	0.0					
43.38	3.735	0.000	117.0	125.8	117.3	106.5	100.9	110.9	93.8	95.8	93.7	84.4	52.5	0.0				
52.48	3.766	0.000	120.2	129.2	120.5	109.7	104.2	113.7	104.8	102.3	101.8	96.9	81.1	68.5	0.0			
64.58	3.776	0.000	124.0	132.7	123.8	113.9	108.5	120.0	110.8	110.0	111.2	106.7	99.3	91.3	70.6	0.0		
73.68	3.776	0.000	126.4	134.8	125.7	115.8	110.6	122.4	114.2	113.5	114.5	111.5	105.4	99.5	84.9	61.4	0.0	
81.58	3.776	0.000	114.3	134.1	118.6	114.3	112.0	125.2	113.2	113.4	117.6	113.9	110.1	105.7	92.7	74.3	51.1	0.0
90.00	-2.633	0.000	48.9	65.7	62.0	61.7	63.6	89.2	91.6	97.5	105.4	106.1	106.2	105.8	95.2	84.1	75.1	84.2
100.00	-1.576	0.000	35.0	50.9	45.9	43.3	44.1	67.7	67.4	75.3	84.9	89.2	91.7	94.5	88.1	86.1	82.2	92.7
110.00	-.709	0.000	28.7	43.4	37.8	33.9	33.7	55.8	54.5	62.1	72.4	76.4	80.9	85.5	79.5	79.6	77.9	90.2
120.00	-.357	0.000	24.4	38.8	32.4	26.8	25.7	45.6	45.3	53.0	63.0	66.3	70.5	74.6	67.5	67.5	62.2	71.9
130.00	-.199	0.000	20.5	35.6	28.7	22.2	20.0	39.1	37.6	43.7	53.0	56.0	60.4	64.8	58.2	56.8	45.9	58.2
140.00	-.090	0.000	16.3	31.8	25.0	17.0	14.4	31.8	28.4	33.5	41.6	43.7	46.8	50.0	41.9	36.9	30.9	43.2
150.00	-.041	0.000	13.1	29.3	21.8	13.3	9.3	25.6	20.2	24.5	31.7	32.1	33.6	35.0	26.0	16.6	11.3	20.9
160.00	-.016	0.000	5.1	25.9	18.3	8.9	4.3	17.2	11.4	16.7	21.3	19.1	19.1	19.3	10.2	0.0	0.0	0.0
170.00	-.012	0.000	0.0	22.6	15.0	5.5	0.0	9.9	3.6	11.3	14.4	7.9	9.4	11.0	2.8	0.0	0.0	0.0
180.00	-.008	0.000	0.0	18.9	11.6	1.7	0.0	2.2	0.0	5.7	6.8	0.0	2.1	3.9	0.0	0.0	0.0	0.0
190.00	0.000	0.000	0.0	15.9	9.1	0.0	0.0	0.0	0.0	.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 52.21 MM M2/M/M
DRAINBACK VOLUME = 9.64 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.768 L/S
INFLOW TIME = 83.05 MIN
AVE. SLOPE = -.00004 M/M
AVE. TOP WIDTH A = 30.599
AVE. TOP WIDTH B = .585
AVE. WET PERIM A = 30.293
AVE. WET PERIM B = .598
AVE. SHAPE PROF = .443
AVE. SHAPE DEPTH = .319
AVE. SHAPE ADVAN = .821

Table 20. Water surface profile data for Test Number 119, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 119

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	14	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	22.17	21.84	18.02	24.13	24.76	12.30	21.22	0.00
*****TOP WIDTH*******								
R^2	.977	.945	.851	.987	.936	.945	.927	.954
*TW=A(D)^B * A	57.712	52.056	19.292	24.294	21.314	16.846	25.956	8.550
TW & D, MM B	.471	.492	.692	.671	.685	.719	.635	.892
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	57.398	51.818	19.288	24.282	21.316	16.880	25.898	8.768
WP & D, MM B	.478	.499	.703	.679	.694	.730	.644	.900
SURF. SHAPE FACT.								
*PROFILE *	.160	.165	.173	.161	.165	.291	.287	.315
*DEPTH *	.210	.217	.227	.211	.217	.224	.192	.304
*ADVANCE *	1.312	1.312	1.312	1.312	1.312	.769	.668	.690

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
1.89	3.137	0.000	52.6	0.0						
2.87	3.151	0.000	79.9	57.2	0.0					
5.43	3.151	0.000	94.3	78.0	71.1	0.0				
7.39	3.145	0.000	99.9	85.4	82.6	59.6	0.0			
17.87	3.122	0.000	109.7	97.1	95.4	86.9	88.3	0.0		
30.27	3.101	0.000	115.5	104.0	102.9	96.4	100.2	85.2	0.0	
46.57	3.101	0.000	125.7	113.2	112.2	106.2	110.3	101.4	78.6	0.0
50.00	.119	0.000	64.2	80.7	86.6	89.4	97.2	96.1	80.4	83.3
60.00	-1.159	0.000	16.2	34.9	40.0	44.8	44.5	60.3	55.2	74.6
70.00	-.119	0.000	7.7	21.1	22.7	26.3	25.1	38.0	31.2	48.0
80.00	-.014	0.000	0.0	3.0	7.4	8.9	8.1	18.8	12.9	24.8
90.00	-.005	0.000	0.0	0.0	0.0	0.0	0.0	.8	0.0	0.0
90.60	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 74.39 MM M2/M/M
DRAINBACK VOLUME = 9.24 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.112 L/S
INFLOW TIME = 48.57 MIN
AVE. SLOPE = -.00014 M/M
AVE. TOP WIDTH A = 24.674
AVE. TOP WIDTH B = .652
AVE. WET PERIM A = 24.573
AVE. WET PERIM B = .662
AVE. SHAPE PROF = .200
AVE. SHAPE DEPTH = .225
AVE. SHAPE ADVAN = .961

Table 21. Water surface profile data for Test Number 120, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 120

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	20	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	12.65	18.80	15.70	19.27	21.34	26.38	20.50	26.09	15.25	14.37	15.63	0.00
*****TOP WIDTH*******												
R^2	.965	.984	.925	.995	.911	.987	.976	.988	.945	.994	.994	.985
*TW=A(D)^B * A	55.624	13.088	47.280	15.594	.094	25.702	11.276	16.572	38.988	10.206	10.338	11.046
TW & D, MM B	.468	.764	.491	.724	1.600	.619	.783	.684	.515	.795	.801	.782
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	55.340	13.172	47.020	15.626	1.960	25.612	11.396	16.560	38.790	10.344	10.482	11.172
WP & D, MM B	.475	.777	.500	.738	1.022	.630	.798	.700	.525	.811	.816	.797
SURF. SHAPE FACT.												
*PROFILE *	.379	.505	.629	.527	.557	.667	.992	.698	.687	.361	.286	.515
*DEPTH *	.141	.188	.234	.196	.208	.492	.562	.389	.429	.212	.223	.804
*ADVANCE *	.373	.373	.373	.373	.373	.738	.566	.558	.624	.587	.780	.619

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.06	2.587	0.000	1.8	0.0										
.39	3.003	0.000	11.9	10.5	0.0									
3.78	3.003	0.000	82.0	76.2	72.1	0.0								
5.68	3.000	0.000	86.7	82.2	80.5	63.6	0.0							
14.48	2.991	0.000	102.5	100.4	102.4	93.9	88.9	0.0						
25.08	2.975	0.000	111.0	109.1	111.1	103.7	99.9	72.8	0.0					
41.68	2.960	0.000	117.5	115.8	118.6	112.8	110.5	91.1	81.1	0.0				
62.18	2.981	0.000	123.1	121.4	124.3	118.0	115.4	105.7	101.5	78.6	0.0			
83.28	2.991	0.000	125.6	124.1	127.1	120.9	118.7	108.2	104.3	86.3	75.4	0.0		
108.28	2.958	0.000	130.1	128.1	131.0	123.8	123.0	106.2	102.8	85.6	84.1	65.8	0.0	
128.50	2.954	0.000	132.8	131.0	131.0	118.2	115.5	103.1	100.3	85.9	84.7	68.9	49.3	0.0
130.00	2.954	0.000	133.2	132.1	131.0	118.1	114.7	102.4	99.7	86.0	84.3	68.2	48.8	10.0
140.00	2.954	0.000	116.5	114.4	122.8	117.0	109.3	96.2	93.0	83.2	82.2	67.5	50.8	30.0
150.00	-2.170	0.000	25.8	37.5	49.0	53.0	58.4	63.0	69.3	63.6	71.8	64.8	53.5	30.0
160.00	-.811	0.000	0.0	20.6	30.2	30.5	34.3	35.6	41.5	37.3	49.4	44.4	38.1	30.0
170.00	-.198	0.000	0.0	8.8	18.2	17.0	19.2	18.7	23.1	16.8	26.5	22.0	16.1	13.4
180.00	-.106	0.000	0.0	0.0	5.1	8.5	10.1	5.7	9.1	0.0	6.3	3.1	0.0	0.0
190.00	-.120	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
192.00	-.068	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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INFLOW VOLUME     =  103.56 MM M2/M/M
DRAINBACK VOLUME =     9.72 MM M2/M/M
RUNOFF VOLUME     =     0.00 MM M2/M/M
AVE. INFLOW RATE =   2.970 L/S
INFLOW TIME       =  141.68 MIN
AVE. SLOPE        = -.00004  M/M
AVE. TOP WIDTH A =  17.131
AVE. TOP WIDTH B =     .686
AVE. WET PERIM A =  17.833
AVE. WET PERIM B =     .692
AVE. SHAPE PROF  =     .572
AVE. SHAPE DEPTH =     .340
AVE. SHAPE ADVAN =     .526
```

Table 22. Water surface profile data for Test Number 121, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 121

NO. STA	NO. TIME PERIODS	FURROW SPACING
14	22	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0
ELEVATIONS, MM	18.95	24.03	27.49	34.02	39.56	26.43	25.63	37.06	22.38	28.68	18.05	0.00	9.44	7.75
*****TOP WIDTH*******														
R^2	.970	.953	.979	.830	.976	.586	.698	.970	.929	.718	.587	.959	.976	.332
*TW=A(D)^B * A	46.974	60.544	23.208	51.348	20.162	4.030	27.674	10.928	.852	87.014	13.295	12.028	20.566	13.806
TW & D, MM B	.503	.467	.628	.490	.678	.962	.599	.732	1.276	.374	.747	.761	.665	.740
*****WETTED PER******														
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	46.774	60.234	23.052	51.729	20.166	4.495	27.500	11.050	2.099	86.435	13.340	12.106	20.498	13.856
WP & D, MM B	.516	.474	.642	.497	.689	.970	.610	.806	1.038	.331	.762	.778	.678	.755
SURF. SHAPE FACT.														
*PROFILE *	.236	.163	.141	.137	.128	.216	.294	.402	.224	.526	.349	.676	.852	0.000
*DEPTH *	.277	.152	.132	.129	.119	.191	.254	.241	.140	.138	.175	.365	.277	.357
*ADVANCE *	.934	.934	.934	.934	.934	.885	.863	.600	.625	.377	.501	.569	.322	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM													
0.00	0.000	0.000	0.0													
2.01	3.039	0.000	59.4	0.0												
4.23	3.052	0.000	74.2	69.4	0.0											
7.20	3.052	0.000	91.3	87.4	84.5	0.0										
14.50	3.052	0.000	103.6	108.2	105.7	91.7	0.0									
20.30	3.051	0.000	115.2	114.2	111.2	88.6	70.7	0.0								
32.10	3.040	0.000	120.6	119.6	116.6	95.3	82.4	69.2	0.0							
44.80	3.023	0.000	122.8	122.2	119.1	99.3	87.2	100.4	78.8	0.0						
65.00	3.005	0.000	126.6	125.8	123.2	103.6	93.2	111.3	97.1	75.7	0.0					
87.00	3.003	0.000	129.8	128.7	126.3	107.7	98.2	118.0	105.5	89.5	84.1	0.0				
131.00	3.003	0.000	131.8	131.0	128.8	110.3	101.3	124.4	113.4	93.8	98.7	72.8	0.0			
171.00	3.003	0.000	133.6	132.0	130.6	112.0	102.8	125.5	115.7	102.2	99.0	78.5	50.1	0.0		
210.30	3.003	0.000	131.8	131.5	129.0	110.8	102.3	124.6	114.6	101.0	103.3	85.3	60.3	56.1	0.0	
291.70	3.003	0.000	138.4	134.9	138.3	106.6	108.8	130.2	120.8	107.2	112.1	94.6	83.0	83.2	71.5	0.0
300.00	-1.506	0.000	28.1	50.6	61.6	73.4	72.1	106.2	102.8	98.0	104.6	90.3	80.6	81.6	74.1	55.9
310.00	-.963	0.000	8.8	30.5	44.0	38.9	49.1	81.0	76.9	70.0	81.9	72.2	70.4	70.8	68.8	69.9
320.00	-.238	0.000	0.0	21.2	34.6	21.9	35.3	65.3	61.0	53.8	63.9	52.2	53.3	53.4	55.5	55.4
330.00	-.041	0.000	0.0	13.8	26.0	2.2	25.5	52.8	47.7	39.2	46.1	29.1	31.5	31.2	33.6	28.2
340.00	-.012	0.000	0.0	7.4	17.6	0.0	17.1	42.7	37.5	26.6	27.8	4.0	8.4	8.0	10.4	4.4
350.00	-.009	0.000	0.0	.1	7.1	0.0	9.1	30.8	24.1	14.4	8.5	0.0	0.0	0.0	0.0	0.0
360.00	-.007	0.000	0.0	0.0	0.0	0.0	.8	19.2	11.7	2.0	0.0	0.0	0.0	0.0	0.0	0.0
363.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	15.9	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 174.25 MM M2/M/M
DRAINBACK VOLUME = 6.45 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.009 L/S
INFLOW TIME = 294.20 MIN
AVE. SLOPE = -.00007 M/M
AVE. TOP WIDTH A = 21.530
AVE. TOP WIDTH B = .651
AVE. WET PERIM A = 21.914
AVE. WET PERIM B = .660
AVE. SHAPE PROF = .339
AVE. SHAPE DEPTH = .217
AVE. SHAPE ADVAN = .842

Table 23. Water surface profile data for Test Number 122, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 122

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	18	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	22.17	21.84	18.02	24.13	24.76	12.30	21.22	0.00
*****TOP WIDTH*******								
R^2	.977	.945	.851	.987	.936	.945	.927	.954
*TW=A(D)^B * A	57.712	52.056	19.292	24.294	21.314	16.846	25.956	8.550
TW & D, MM B	.471	.492	.692	.671	.685	.719	.635	.892
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	57.398	51.818	19.288	24.282	21.316	16.880	25.898	8.768
WP & D, MM B	.478	.499	.703	.679	.694	.730	.644	.900
SURF. SHAPE FACT.								
*PROFILE *	.198	.243	.220	.232	.314	.262	.323	.402
*DEPTH *	.187	.230	.208	.220	.298	.199	.225	.296
*ADVANCE *	.948	.948	.948	.948	.948	.759	.697	.600

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.52	2.955	0.000	19.4	0.0						
1.08	3.003	0.000	40.3	30.4	0.0					
2.27	3.003	0.000	74.9	59.4	55.9	0.0				
3.44	3.005	0.000	80.8	66.8	63.6	24.0	0.0			
9.07	3.028	0.000	96.0	83.9	82.3	73.3	64.5	0.0		
15.47	3.070	0.000	103.2	92.3	91.2	84.8	78.4	75.2	0.0	
23.37	3.119	0.000	94.8	92.5	93.4	90.5	86.4	89.7	68.7	0.0
30.00	-1.662	0.000	23.8	37.6	44.6	50.3	51.6	69.5	66.6	85.8
40.00	-.471	0.000	10.1	26.2	32.4	34.6	35.7	51.1	48.0	66.7
50.00	-.152	0.000	7.8	20.6	25.0	26.3	27.6	42.9	39.0	57.7
60.00	-.052	0.000	5.4	17.6	19.8	20.3	20.1	33.7	29.2	47.6
70.00	-.014	0.000	0.0	11.8	13.4	13.1	12.0	26.8	21.7	38.8
80.00	-.007	0.000	0.0	4.0	6.3	5.2	4.7	19.9	14.4	30.1
90.00	-.005	0.000	0.0	0.0	.9	0.0	0.0	11.8	7.3	20.4
100.00	-.004	0.000	0.0	0.0	0.0	0.0	0.0	3.0	.4	11.6
110.00	-.003	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
110.40	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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INFLOW VOLUME    =   36.34 MM M2/M/M
DRAINBACK VOLUME =   10.00 MM M2/M/M
RUNOFF VOLUME    =    0.00 MM M2/M/M
AVE. INFLOW RATE =   3.068 L/S
INFLOW TIME      =   24.07 MIN
AVE. SLOPE       = -.00014  M/M
AVE. TOP WIDTH A =  24.674
AVE. TOP WIDTH B =    .652
AVE. WET PERIM A =  24.573
AVE. WET PERIM B =    .662
AVE. SHAPE PROF  =    .256
AVE. SHAPE DEPTH =    .233
AVE. SHAPE ADVAN =    .830
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Table 24. Water surface profile data for Test Number 123, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 123

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	23	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	12.65	18.80	15.70	19.27	21.34	26.38	20.50	26.09	15.25	14.37	15.63	0.00
*****TOP WIDTH*******												
R^2	.955	.984	.925	.996	.911	.987	.976	.988	.945	.994	.994	.985
*TW=A(D)^B * A	55.624	13.088	47.280	15.594	.094	25.702	11.276	16.572	38.988	10.206	10.338	11.046
TW & D, MM B	.468	.764	.491	.724	1.600	.619	.783	.684	.515	.795	.801	.782
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	55.340	13.172	47.020	15.626	1.960	25.612	11.396	16.560	38.790	10.344	10.482	11.172
WP & D, MM B	.475	.777	.500	.738	1.022	.630	.798	.700	.525	.811	.816	.797
SURF. SHAPE FACT.												
*PROFILE *	.593	1.000	.592	.482	.423	.218	.375	.378	.390	.695	.551	1.000
*DEPTH *	.231	.557	.231	.188	.165	.207	.277	.291	.317	.461	.323	.184
*ADVANCE *	.390	.390	.390	.390	.390	.947	.739	.768	.811	.663	.587	.134

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.05	2.497	0.000	1.9	0.0										
.42	2.954	0.000	14.5	11.3	0.0									
2.45	2.954	0.000	68.0	60.7	53.9	0.0								
3.67	2.954	0.000	77.2	71.0	73.1	59.7	0.0							
9.17	2.954	0.000	91.7	90.2	92.7	85.0	81.6	0.0						
14.07	2.954	0.000	98.9	97.2	100.4	93.4	90.8	66.5	0.0					
20.77	2.954	0.000	104.5	103.5	107.0	100.2	98.6	79.8	68.2	0.0				
27.77	2.954	0.000	108.7	108.7	111.1	104.1	103.7	87.7	81.9	61.4	0.0			
34.77	2.964	0.000	111.7	111.0	114.3	107.9	107.1	92.6	88.4	69.4	59.9	0.0		
43.87	2.993	0.000	114.7	114.0	117.5	111.1	109.7	97.3	94.0	78.0	76.3	56.2	0.0	
55.07	3.029	0.000	107.2	110.0	114.7	113.0	111.4	101.1	99.5	84.9	86.5	72.8	54.9	0.0
60.00	-1.971	0.000	43.3	54.3	67.1	73.5	80.9	82.4	89.4	81.1	87.1	77.8	64.8	60.6
70.00	-1.239	0.000	15.0	32.5	42.7	43.9	48.1	52.7	61.2	58.7	72.8	70.8	66.7	69.2
80.00	-.334	0.000	6.0	27.0	36.0	35.0	38.0	41.6	50.2	47.9	60.9	58.8	54.1	57.3
90.00	-.143	0.000	0.0	23.6	31.2	28.7	30.8	32.8	41.8	38.0	51.0	48.3	43.4	46.2
100.00	-.060	0.000	0.0	18.7	26.3	23.1	24.5	24.8	32.8	29.4	43.1	40.5	35.9	37.6
110.00	-.019	0.000	0.0	8.9	18.1	17.3	18.1	16.6	24.1	21.2	33.0	31.4	26.5	28.5
120.00	-.007	0.000	0.0	0.0	8.2	11.7	13.6	7.4	15.3	11.1	23.0	20.3	14.9	15.0
130.00	-.004	0.000	0.0	0.0	0.0	7.2	9.3	0.0	7.8	3.0	12.6	11.7	5.3	2.8
140.00	-.002	0.000	0.0	0.0	0.0	1.5	4.7	0.0	0.0	0.0	1.4	.5	0.0	0.0
150.00	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
150.60	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 41.46 MM M2/M/M
DRAINBACK VOLUME = 7.97 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 2.978 L/S
INFLOW TIME = 56.57 MIN
AVE. SLOPE = -.00004 M/M
AVE. TOP WIDTH A = 17.131
AVE. TOP WIDTH B = .686
AVE. WET PERIM A = 17.893
AVE. WET PERIM B = .692
AVE. SHAPE PROF = .518
AVE. SHAPE DEPTH = .286
AVE. SHAPE ADVAN = .595

Table 25. Water surface profile data for Test Number 124, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 124

NO. STA	NO. TIME PERIODS	FURROW SPACING
14	27	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0
ELEVATIONS, MM	18.95	24.09	27.49	34.02	33.56	26.43	25.63	37.06	22.38	28.68	18.05	0.00	9.44	7.75
*****TOP WIDTH*******														
R^2	.970	.953	.979	.830	.976	.585	.698	.970	.929	.718	.987	.959	.976	.982
*TW=A(D)^B * A	46.974	60.544	23.209	51.349	20.162	4.030	27.674	10.929	.852	87.014	13.236	12.028	20.566	13.606
TW & D, MM B	.509	.467	.628	.490	.678	.952	.598	.792	1.276	.374	.747	.761	.665	.740
****WETTED PER******														
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	46.774	60.234	23.032	51.728	20.156	4.496	27.500	11.050	2.038	86.436	13.340	12.106	20.498	13.856
WP & D, MM B	.516	.474	.642	.497	.689	.970	.610	.806	1.038	.381	.762	.778	.678	.755
SURF. SHAPE FACT.														
*PROFILE *	.128	.021	.017	.042	.037	.205	.271	.473	.296	.431	.138	.429	.437	.183
*DEPTH *	.759	.122	.100	.251	.220	.182	.250	.319	.204	.215	.318	.215	.301	.326
*ADVANCE *	5.932	5.932	5.932	5.932	5.932	.889	.922	.675	.697	.439	2.301	.502	.607	.723

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM													
0.00	0.000	0.000	0.0													
2.96	3.043	0.000	64.2	0.0												
3.33	3.052	0.000	68.4	67.9	0.0											
3.40	3.053	0.000	69.3	69.7	65.6	0.0										
4.00	3.053	0.000	76.2	75.4	72.7	37.5	0.0									
9.00	3.058	0.000	99.9	97.3	94.6	73.5	53.0	0.0								
14.20	3.067	0.000	104.7	103.5	101.3	81.5	63.9	78.4	0.0							
19.40	3.076	0.000	107.6	107.4	104.9	85.6	75.8	89.3	68.7	0.0						
27.00	3.088	0.000	112.7	111.7	109.4	90.9	81.9	100.3	86.5	63.9	0.0					
35.20	3.094	0.000	115.9	114.9	112.7	94.7	87.9	107.7	97.5	79.7	76.5	0.0				
50.01	3.049	0.000	118.7	117.9	115.9	98.3	90.9	112.8	103.6	89.1	91.4	68.0	0.0			
53.00	3.011	0.000	119.1	118.4	116.6	99.3	91.7	114.0	104.6	90.4	93.2	71.7	54.3	0.0		
67.00	2.975	0.000	122.1	121.1	119.3	102.1	94.7	117.5	109.0	95.7	100.8	83.1	88.9	93.9	0.0	
79.70	2.954	0.000	125.9	122.6	121.5	106.8	97.2	121.2	112.6	100.3	105.6	90.0	97.3	105.2	71.3	0.0
80.00	2.954	0.000	125.2	122.6	121.8	105.6	97.3	120.7	112.7	100.3	106.5	90.2	97.5	105.3	71.7	5.7
90.00	-2.053	0.000	55.8	37.7	47.8	52.6	54.7	89.7	87.7	81.9	94.7	86.0	98.1	111.1	85.9	85.1
100.00	-.897	0.000	9.6	26.6	35.7	33.5	38.1	70.9	68.8	64.1	77.9	70.8	88.8	106.8	89.2	90.4
110.00	-.316	0.000	0.0	21.4	30.0	33.6	30.3	61.1	58.8	53.0	66.0	58.6	77.1	94.4	77.3	79.3
120.00	-.124	0.000	0.0	17.0	25.5	28.8	24.0	54.3	51.1	44.7	57.6	50.2	68.4	86.3	68.7	70.8
130.00	-.032	0.000	0.0	12.4	20.9	24.0	18.9	47.5	43.5	36.8	48.9	40.9	59.3	75.3	57.8	58.7
140.00	-.011	0.000	0.0	7.5	15.1	17.6	13.0	40.1	36.7	30.7	41.8	32.5	50.9	68.7	52.0	53.7
150.00	-.007	0.000	0.0	2.8	8.3	10.9	6.5	32.7	30.2	24.7	35.0	21.0	39.5	59.4	42.0	43.3
160.00	-.005	0.000	0.0	0.0	1.6	3.8	0.0	26.0	21.7	15.2	22.4	3.9	23.2	42.9	28.8	26.2
170.00	-.005	0.000	0.0	0.0	0.0	0.0	0.0	19.2	14.2	8.4	11.3	0.0	16.1	32.2	19.9	12.8
180.00	-.004	0.000	0.0	0.0	0.0	0.0	0.0	11.9	6.5	.8	1.5	0.0	13.9	28.5	13.4	4.0
190.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	7.5	15.5	.1	0.0
190.20	0.000	0.000	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	7.4	15.4	0.0	0.0

INFLOW VOLUME = 48.89 MM M2/M/M
DRAINBACK VOLUME = 7.97 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.029 L/S
INFLOW TIME = 82.00 MIN
AVE. SLOPE = -.00007 M/M
AVE. TOP WIDTH A = 21.530
AVE. TOP WIDTH B = .651
AVE. WET PERIM A = 21.914
AVE. WET PERIM B = .660
AVE. SHAPE PROF = .234
AVE. SHAPE DEPTH = .270
AVE. SHAPE ADVAN = 1.036

Table 26. Water surface profile data for Test Number 125, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 125

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	15	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	22.17	21.84	18.02	24.13	24.76	12.30	21.22	0.00
*****TOP WIDTH********								
R^2	.977	.945	.851	.987	.936	.945	.927	.954
*TW=A(D)^B * A	57.712	52.056	19.292	24.294	21.314	16.846	25.956	8.550
TW & D, MM B	.471	.492	.692	.671	.685	.719	.635	.892
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	57.398	51.818	19.288	24.282	21.316	16.880	25.898	8.768
WP & D, MM B	.478	.493	.703	.679	.694	.730	.644	.900
SURF. SHAPE FACT.								
*PROFILE *	.395	.486	.526	1.000	.580	.666	.965	.473
*DEPTH *	.176	.217	.234	.466	.259	.494	.601	.113
*ADVANCE *	.446	.446	.446	.446	.446	.742	.623	.675

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.07	2.642	0.000	2.3	0.0						
.33	3.003	0.000	11.1	8.8	0.0					
1.56	3.003	0.000	52.7	41.8	37.9	0.0				
3.87	3.012	0.000	81.0	68.4	65.2	46.6	0.0			
8.38	3.033	0.000	92.3	80.7	79.5	71.2	60.8	0.0		
14.48	3.052	0.000	98.9	88.1	87.4	81.0	74.4	70.0	0.0	
22.98	3.052	0.000	99.9	91.9	92.4	88.2	85.3	86.1	64.2	0.0
30.00	-1.519	0.000	24.9	33.1	41.2	45.7	47.1	63.1	60.4	80.5
40.00	-.469	0.000	15.6	22.9	29.3	31.3	31.5	46.0	41.7	60.8
50.00	-.148	0.000	11.2	17.5	22.1	22.3	22.7	35.6	30.7	49.3
60.00	-.043	0.000	7.2	13.1	16.0	14.9	14.6	27.8	23.0	41.3
70.00	-.011	0.000	0.0	5.4	8.4	6.4	7.4	18.8	15.9	30.7
80.00	-.007	0.000	0.0	.0	3.6	1.5	1.4	12.1	6.8	19.5
87.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	.4	.1	2.7

INFLOW VOLUME	=	35.58 MM M2/M/M
DRAINBACK VOLUME	=	9.80 MM M2/M/M
RUNOFF VOLUME	=	0.00 MM M2/M/M
AVE. INFLOW RATE	=	3.040 L/S
INFLOW TIME	=	23.78 MIN
AVE. SLOPE	=	-.00014 M/M
AVE. TOP WIDTH A	=	24.674
AVE. TOP WIDTH B	=	.652
AVE. WET PERIM A	=	24.573
AVE. WET PERIM B	=	.662
AVE. SHAPE PROF	=	.660
AVE. SHAPE DEPTH	=	.320
AVE. SHAPE ADVAN	=	.548

Table 27. Water surface profile data for Test Number 126, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 126

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	21	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	12.65	18.80	15.70	19.27	21.34	26.38	20.50	26.09	15.25	14.37	15.63	0.00
*****TOP WIDTH*******												
R^2	.955	.984	.925	.996	.911	.987	.976	.988	.945	.994	.994	.985
*TW=A(D)^B * A	55.624	13.088	47.280	15.594	.094	25.702	11.276	16.572	38.998	10.206	10.338	11.046
TW & D, MM B	.468	.764	.491	.724	1.600	.619	.783	.684	.515	.795	.801	.782
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	55.340	13.172	47.020	15.626	1.960	25.612	11.396	16.560	38.790	10.344	10.482	11.172
WP & D, MM B	.475	.777	.500	.738	1.022	.630	.798	.700	.525	.811	.816	.797
SURF. SHAPE FACT.												
*PROFILE *	.482	.546	.623	.515	.583	.025	1.000	.287	.552	.166	.728	.429
*DEPTH *	.231	.262	.299	.247	.279	.161	.511	.196	.351	.157	.507	.331
*ADVANCE *	.479	.479	.479	.479	.479	6.369	.489	.683	.637	.944	.696	.502

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.07	2.701	0.000	2.4	0.0										
.31	3.052	0.000	10.4	9.2	0.0									
2.05	3.052	0.000	60.6	56.7	55.7	0.0								
3.04	3.052	0.000	65.3	61.7	61.3	21.4	0.0							
10.65	3.052	0.000	89.8	88.9	96.2	83.2	83.1	0.0						
11.35	3.052	0.000	91.0	90.5	99.3	84.9	85.1	50.0	0.0					
20.45	3.052	0.000	102.6	100.9	110.8	104.7	103.7	76.2	62.4	0.0				
28.35	3.056	0.000	108.7	107.3	116.5	113.0	110.2	85.5	80.0	56.3	0.0			
37.75	3.084	0.000	113.6	112.5	121.9	118.9	116.2	93.3	90.4	70.9	64.6	0.0		
44.45	3.101	0.000	115.2	114.4	122.3	118.8	118.7	96.4	95.7	77.4	74.0	52.9	0.0	
53.85	3.101	0.000	117.8	116.0	114.3	110.0	111.3	99.3	98.4	83.2	82.3	68.2	55.2	0.0
60.00	-1.452	0.000	43.3	53.3	72.5	73.6	75.8	80.1	87.2	79.5	86.5	76.7	69.4	67.6
70.00	-1.349	0.000	18.4	33.7	42.7	42.3	46.5	50.8	58.9	56.2	69.1	67.3	66.9	69.3
80.00	-.409	0.000	10.0	28.0	36.4	34.2	37.3	40.2	48.0	43.9	55.4	51.7	55.1	59.1
90.00	-.178	0.000	4.4	23.9	31.4	28.3	30.1	31.5	38.7	34.3	45.9	41.9	46.3	49.9
100.00	-.066	0.000	0.0	20.1	26.8	23.1	24.2	24.1	30.5	26.1	39.9	37.8	34.9	41.3
110.00	-.019	0.000	0.0	14.1	20.9	18.5	19.1	15.8	22.5	18.8	32.0	29.6	29.4	31.0
120.00	-.010	0.000	0.0	3.6	10.9	11.7	13.1	6.9	13.5	8.0	20.1	18.1	14.0	18.0
130.00	-.007	0.000	0.0	0.0	2.4	7.7	8.6	0.0	6.7	.7	10.8	7.2	6.4	3.6
138.00	0.000	0.000	0.0	0.0	0.0	2.4	5.0	0.0	1.3	0.0	1.6	0.0	0.0	0.0

INFLOW VOLUME = 41.86 MM M2/M/M
DRAINBACK VOLUME = 8.36 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.073 L/S
INFLOW TIME = 55.35 MIN
AVE. SLOPE = -.00004 M/M
AVE. TOP WIDTH A = 17.131
AVE. TOP WIDTH B = .686
AVE. WET PERIM A = 17.893
AVE. WET PERIM B = .692
AVE. SHAPE PROF = .501
AVE. SHAPE DEPTH = .294
AVE. SHAPE ADVAN = .601

Table 28. Water surface profile data for Test Number 127, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 127

NO. STA	NO. TIME PERIODS	FURROW SPACING
14	24	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0
ELEVATIONS, MM	18.95	24.09	27.49	34.02	33.56	26.43	25.63	37.06	22.38	28.68	18.05	0.00	9.44	7.75
*****TOP WIDTH*******														
R^2	.970	.963	.979	.830	.976	.586	.698	.970	.929	.718	.997	.959	.976	.982
*TW=A(D)^B * A	46.974	60.544	23.208	51.948	20.182	4.030	27.674	10.928	.852	67.014	13.286	12.028	20.566	13.806
TW & D, MM B	.509	.467	.628	.490	.678	.952	.593	.792	1.275	.374	.747	.761	.665	.740
*****WETTED PER******														
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	46.774	60.234	23.032	51.728	20.166	4.496	27.500	11.050	2.038	85.436	13.340	12.106	20.498	13.856
WP & D, MM B	.516	.474	.642	.497	.689	.970	.610	.805	1.098	.381	.752	.778	.678	.755
SURF. SHAPE FACT.														
*PROFILE *	.189	.111	.030	.093	.032	.284	.260	.670	.170	.486	.605	.370	.436	0.000
*DEPTH *	.337	.139	.162	.165	.165	.231	.285	.369	.145	.361	.298	.326	.277	.306
*ADVANCE *	1.785	1.785	1.785	1.785	1.785	.814	1.036	.551	.851	.742	.493	.891	.558	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM													
0.00	0.000	0.000	0.0													
1.89	3.039	0.000	43.6	0.0												
2.45	3.052	0.000	56.4	51.7	0.0											
4.11	3.052	0.000	70.0	66.0	61.9	0.0										
5.16	3.052	0.000	77.8	73.5	70.1	41.6	0.0									
9.92	3.052	0.000	92.4	83.5	87.7	65.6	50.9	0.0								
16.32	3.052	0.000	100.1	96.1	94.4	73.6	61.5	66.8	0.0							
21.22	3.052	0.000	103.0	99.5	97.7	77.2	66.4	76.4	53.6	0.0						
31.82	3.052	0.000	107.6	104.1	102.7	82.9	73.4	88.6	73.4	52.8	0.0					
39.42	3.052	0.000	110.4	107.1	105.5	86.2	77.4	94.6	81.8	65.4	62.4	0.0				
48.52	3.052	0.000	113.3	109.8	108.2	89.3	81.0	99.3	88.0	73.3	74.0	48.5	0.0			
63.62	3.052	0.000	116.5	113.1	111.6	93.0	84.9	104.0	93.5	80.2	83.3	62.9	61.7	0.0		
72.72	3.052	0.000	117.8	114.7	113.2	94.6	85.8	106.2	96.5	84.1	88.5	70.7	72.7	48.6	0.0	
87.82	3.052	0.000	121.4	110.8	113.5	94.1	86.8	107.8	98.9	87.5	92.7	77.0	79.5	68.7	56.9	0.0
90.00	-1.434	0.000	91.2	95.7	92.6	81.9	78.2	103.8	98.0	85.6	92.5	77.4	79.2	69.6	59.8	30.7
100.00	-2.047	0.000	16.0	32.1	41.3	41.2	41.1	70.7	66.5	61.3	72.7	63.6	73.4	71.9	69.1	62.9
110.00	-.461	0.000	9.3	23.5	32.3	31.7	28.4	56.5	52.5	46.8	59.3	52.3	63.7	66.2	68.0	63.5
120.00	-.146	0.000	5.4	17.5	26.8	25.3	20.6	47.6	42.6	36.6	47.8	40.7	53.2	54.4	57.8	50.8
130.00	-.039	0.000	2.5	12.8	22.7	20.0	14.5	40.3	35.4	29.4	40.3	31.7	42.9	45.1	47.2	42.1
140.00	-.008	0.000	0.0	8.7	17.5	13.9	8.4	33.2	28.1	21.6	31.1	22.0	32.3	35.5	37.4	33.3
150.00	-.005	0.000	0.0	5.1	12.8	7.9	3.0	26.8	21.8	16.5	24.4	10.3	20.6	24.1	27.1	21.5
160.00	-.004	0.000	0.0	.8	6.5	1.0	0.0	19.5	13.7	6.8	12.5	0.0	7.9	12.1	16.5	9.3
170.00	-.003	0.000	0.0	0.0	0.0	0.0	0.0	11.1	5.0	0.0	.7	0.0	0.0	2.0	4.5	.3
180.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

missing 15 & 16 ?

INFLOW VOLUME = 53.23 MM M2/M/M
DRAINBACK VOLUME = 6.44 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.052 L/S
INFLOW TIME = 88.62 MIN
AVE. SLOPE = -.00007 M/M
AVE. TOP WIDTH A = 21.530
AVE. TOP WIDTH B = .651
AVE. WET PERIM A = 21.914
AVE. WET PERIM B = .660
AVE. SHAPE PROF = .301
AVE. SHAPE DEPTH = .259
AVE. SHAPE ADVAN = .933

Table 29. Water surface profile data for Test Number 128, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 128

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	15	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		21.79	19.71	20.65	10.76	10.15	0.00	13.50	15.87
*****TOP WIDTH*******									
	R^2	.990	.984	.984	.992	.943	.953	.963	.991
*TW=A(D)^B *	A	53.300	72.452	40.224	19.202	33.318	50.788	45.340	19.080
TW & D, MM	B	.489	.411	.542	.684	.552	.479	.516	.683
*****WETTED PER*******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	53.102	72.168	40.048	19.182	33.100	50.462	45.128	19.066
WP & D, MM	B	.495	.417	.550	.696	.564	.488	.523	.695
SURF. SHAPE FACT.									
*PROFILE	*	.200	.167	.157	.167	.364	.247	.184	.670
*DEPTH	*	.236	.197	.185	.197	.429	.189	.132	.407
*ADVANCE	*	1.178	1.178	1.178	1.178	1.178	.762	.713	.551

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.83	3.738	0.000	57.7	0.0						
1.31	3.776	0.000	69.2	53.1	0.0					
2.69	3.776	0.000	86.2	73.6	65.1	0.0				
3.80	3.776	0.000	92.3	82.9	78.1	56.8	0.0			
12.53	3.776	0.000	109.4	102.4	103.5	103.4	101.1	0.0		
21.33	3.776	0.000	116.7	110.2	111.5	112.8	111.6	105.9	0.0	
31.93	3.776	0.000	121.6	115.2	116.1	118.9	118.2	119.9	89.3	0.0
40.00	3.776	0.000	126.8	120.1	119.0	122.2	121.4	127.3	106.3	95.7
50.00	-1.043	0.000	29.6	40.6	52.8	71.7	79.9	106.9	96.9	90.2
60.00	-.743	0.000	16.0	23.7	31.6	45.2	52.3	77.0	65.1	57.7
70.00	-.131	0.000	6.9	12.9	17.5	26.7	32.7	57.2	44.6	37.0
80.00	-.016	0.000	0.0	0.0	0.0	8.9	16.2	38.4	24.3	12.1
90.00	-.009	0.000	0.0	0.0	0.0	0.0	1.2	22.8	.5	0.0
97.80	0.000	0.000	0.0	0.0	0.0	0.0	0.0	14.7	0.0	0.0

INFLOW VOLUME = 80.51 MM M2/M/M
DRAINBACK VOLUME = 15.77 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.775 L/S
INFLOW TIME = 43.33 MIN
AVE. SLOPE = -.00006 M/M
AVE. TOP WIDTH A = 39.068
AVE. TOP WIDTH B = .539
AVE. WET PERIM A = 38.765 — 35.22
AVE. WET PERIM B = .549 0.583
AVE. SHAPE PROF = .212
AVE. SHAPE DEPTH = .246
AVE. SHAPE ADVAN = .822

Table 30. Water surface profile data for Test Number 129, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 129

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	22	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	39.50	33.90	29.56	33.88	30.21	34.54	43.50	49.48	39.75	34.54	23.79	0.00
*****TOP WIDTH*******												
R^2	.975	.932	.977	.928	.956	.973	.986	.989	.983	.956	.978	.974
*TW=A(D)^B * A	9.530	9.976	4.412	7.032	6.258	23.212	7.338	9.392	17.484	49.390	23.522	13.284
TW & D, MM B	.824	.808	.974	.848	.908	.645	.863	.825	.704	.485	.635	.756
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	9.754	10.122	4.842	7.276	6.558	23.154	7.578	9.560	17.490	49.146	23.460	13.364
WP & D, MM B	.838	.823	.979	.867	.920	.656	.879	.839	.717	.493	.646	.770
SURF. SHAPE FACT.												
*PROFILE *	.321	.340	.391	.730	1.000	.148	.398	.261	.279	.138	.088	0.000
*DEPTH *	.169	.180	.201	.386	.829	.131	.240	.158	.171	.095	.068	.397
*ADVANCE *	.528	.528	.528	.528	.528	.802	.603	.604	.614	.693	.767	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.20	3.619	0.000	2.7	0.0										
.70	3.776	0.000	16.0	15.3	0.0									
2.61	3.776	0.000	66.7	73.3	66.3	0.0								
5.62	3.776	0.000	86.4	100.4	96.8	53.4	0.0							
15.60	3.776	0.000	104.8	122.0	121.8	116.1	108.8	0.0						
24.70	3.775	0.000	110.1	127.6	127.8	118.3	117.7	91.7	0.0					
39.80	3.755	0.000	116.4	135.1	135.0	125.6	126.5	106.9	82.0	0.0				
57.60	3.726	0.000	122.7	142.3	142.3	132.8	134.8	121.0	101.3	82.4	0.0			
77.50	3.722	0.000	127.3	147.1	146.8	138.3	140.6	128.4	110.5	95.1	84.5	0.0		
96.80	3.722	0.000	129.8	149.7	149.5	141.1	144.1	132.2	115.8	102.3	97.2	84.6	0.0	
115.20	3.722	0.000	131.8	151.2	151.3	143.0	145.3	134.7	118.7	106.3	102.7	92.3	78.8	0.0
120.00	3.722	0.000	131.9	151.5	151.6	143.1	145.6	135.3	118.7	106.1	101.4	91.0	79.5	61.6
130.00	3.722	0.000	132.6	152.1	152.3	144.3	146.5	137.6	121.1	109.0	105.8	97.0	90.6	95.6
140.00	3.722	0.000	127.9	145.3	145.6	148.3	148.6	132.3	121.8	110.6	109.5	103.6	103.5	111.8
150.00	-2.668	0.000	36.1	67.7	75.5	77.1	90.9	102.5	92.3	90.4	97.6	99.8	104.6	114.6
160.00	-.860	0.000	19.5	52.0	60.5	59.7	71.9	78.4	69.8	66.4	71.9	72.8	77.1	87.0
170.00	-.235	0.000	9.3	41.4	50.1	46.4	57.2	61.5	52.0	48.2	54.1	56.0	60.1	69.8
180.00	-.037	0.000	0.0	28.4	38.1	32.7	43.6	47.0	36.8	33.2	34.5	34.8	37.3	48.0
190.00	-.004	0.000	0.0	2.7	20.2	16.4	31.3	32.3	20.3	9.6	10.7	9.1	5.9	17.6
200.00	-.002	0.000	0.0	0.0	0.0	.1	17.8	14.7	.6	0.0	0.0	0.0	0.0	0.0
201.60	0.000	0.000	0.0	0.0	0.0	0.0	15.8	12.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 129.78 MM M2/M/M
DRAINBACK VOLUME = 10.47 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.735 L/S
INFLOW TIME = 141.20 MIN
AVE. SLOPE = -.00007 M/M
AVE. TOP WIDTH A = 12.673
AVE. TOP WIDTH B = .760
AVE. WET PERIM A = 12.731 — 12.15
AVE. WET PERIM B = .776 .792
AVE. SHAPE PROF = .371
AVE. SHAPE DEPTH = .252
AVE. SHAPE ADVAN = .617

Table 31. Water surface profile data for Test Number 130, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 130

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	28	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM		22.27	28.41	12.31	3.84	7.88	41.03	13.03	42.70	40.78	15.03	18.42	6.42	12.84	13.17	13.92	0.00
*****TOP WIDTH*******																	
	R^2	.891	.844	.975	.972	.988	.917	.876	.977	.974	.987	.578	.939	.946	.985	.978	.985
*TW=A(D)^B *	A	104.988	107.560	44.840	35.316	32.664	42.030	30.532	22.302	33.350	25.360	25.612	4.174	17.368	37.104	22.844	37.772
TW & D, MM	B	.361	.346	.523	.557	.586	.548	.596	.667	.597	.634	.637	.973	.716	.556	.650	.543
*****WETTED PER******																	
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	104.768	107.276	44.712	35.198	32.580	41.930	30.516	22.234	33.302	25.320	25.574	4.628	18.002	36.974	22.802	37.606
WP & D, MM	B	.365	.350	.530	.565	.594	.554	.604	.676	.604	.643	.646	.979	.726	.565	.661	.552
SURF. SHAPE FACT.																	
*PROFILE	*	.173	.171	.197	.162	.241	.321	.143	.088	.171	.410	.335	.613	.211	.368	.339	0.000
*DEPTH	*	.220	.218	.251	.207	.307	.151	.092	.081	.149	.336	.252	.237	.089	.177	.294	.284
*ADVANCE	*	1.275	1.275	1.275	1.275	1.275	.472	.642	.924	.875	.820	.751	.386	.424	.483	.866	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.89	3.687	0.000	33.7	0.0														
1.53	3.722	0.000	58.0	45.8	0.0													
2.63	3.722	0.000	65.4	55.8	47.8	0.0												
3.62	3.722	0.000	69.8	60.9	56.2	43.2	0.0											
11.10	3.714	0.000	92.5	87.4	100.5	97.0	84.0	0.0										
26.20	3.693	0.000	111.0	106.5	120.6	120.7	112.5	80.6	0.0									
41.00	3.670	0.000	117.9	113.5	127.7	128.7	120.8	92.1	96.8	0.0								
52.20	3.668	0.000	121.9	117.3	132.8	131.0	126.0	98.3	106.5	69.9	0.0							
64.30	3.668	0.000	123.6	119.4	133.8	134.8	127.9	101.7	111.0	77.4	59.6	0.0						
77.60	3.671	0.000	125.8	121.5	136.0	137.3	130.3	104.8	113.5	81.7	65.6	66.6	0.0					
92.70	3.681	0.000	127.1	123.0	137.9	138.8	132.1	106.8	115.9	85.8	71.2	78.4	57.4	0.0				
125.80	3.699	0.000	129.7	125.6	140.0	141.5	134.6	109.7	120.0	90.9	79.8	92.5	80.4	85.3	0.0			
161.30	3.724	0.000	132.6	128.5	143.2	144.3	137.7	113.8	124.1	97.2	87.0	101.0	90.2	96.8	80.7	0.0		
196.50	3.751	0.000	134.2	130.1	144.7	146.0	133.5	115.5	126.5	99.1	91.9	106.1	96.6	103.8	89.0	70.4	0.0	
213.10	3.757	0.000	135.1	130.9	145.8	146.8	140.2	116.5	127.8	100.9	91.0	107.2	97.5	105.3	90.5	71.5	47.2	0.0
220.00	3.722	0.000	135.3	131.3	146.1	147.1	140.3	116.8	128.0	101.4	92.2	107.7	98.3	106.5	91.7	73.1	49.3	57.0
230.00	3.722	0.000	135.6	131.5	146.0	146.9	140.7	118.3	128.5	101.3	93.3	109.5	100.8	108.8	94.6	78.1	58.7	78.2
240.00	3.722	0.000	119.9	124.0	131.8	142.3	136.9	112.1	123.1	102.9	94.0	110.9	101.6	109.4	96.7	83.8	69.1	90.4
250.00	-2.811	0.000	28.3	33.2	67.2	79.3	80.7	77.1	96.0	81.6	79.7	101.0	94.1	103.9	94.1	86.8	75.3	96.8
260.00	-1.318	0.000	20.7	24.1	48.1	56.5	56.6	48.5	74.3	57.1	56.8	80.3	77.9	90.7	83.8	82.3	74.4	95.5
270.00	-.454	0.000	10.8	15.9	37.7	42.9	41.1	30.6	60.1	41.9	40.4	63.4	60.1	74.2	68.2	64.2	57.3	78.8
280.00	-.116	0.000	3.9	9.6	30.4	33.3	29.1	17.4	48.0	28.6	26.0	48.4	44.5	58.1	52.3	45.5	38.5	59.9
290.00	-.021	0.000	0.0	2.9	22.9	25.9	21.0	6.9	37.4	15.6	11.7	33.4	29.7	42.5	36.3	26.8	18.4	41.1
300.00	-.008	0.000	0.0	0.0	12.7	17.9	13.3	0.0	24.1	1.2	0.0	14.8	13.0	24.7	17.7	0.0	0.0	16.0
310.00	-.006	0.000	0.0	0.0	2.5	9.1	5.4	0.0	11.2	0.0	0.0	0.0	0.0	5.3	0.0	0.0	0.0	0.0
320.00	-.005	0.000	0.0	0.0	0.0	.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320.40	-.004	0.000	0.0	0.0	0.0	.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 150.24 MM M2/M/M
DRAINBACK VOLUME = 9.58 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.711 L/S
INFLOW TIME = 242.70 MIN
AVE. SLOPE = -.00003 M/M
AVE. TOP WIDTH A = 33.790
AVE. TOP WIDTH B = .578
AVE. WET PERIM A = 33.517
AVE. WET PERIM B = .588
AVE. SHAPE PROF = .263
AVE. SHAPE DEPTH = .209
AVE. SHAPE ADVAN = .723

Table 32. Water surface profile data for Test Number 131, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 131

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	21	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	21.79	19.71	19.64	10.76	10.15	0.00	13.50	15.87
*****TOP WIDTH*******								
R^2	.990	.984	.984	.992	.943	.953	.963	.991
*TW=A(D)^B * A	53.300	72.452	40.224	19.202	33.318	50.788	45.340	19.080
TW & D, MM B	.489	.411	.542	.684	.552	.479	.516	.683
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	53.102	72.168	40.048	19.182	33.100	50.462	45.128	19.066
WP & D, MM B	.495	.417	.550	.696	.564	.488	.523	.695
SURF. SHAPE FACT.								
*PROFILE *	.051	.031	.042	.037	.041	.149	.666	.088
*DEPTH *	.226	.135	.183	.162	.183	.195	.382	.316
*ADVANCE *	4.399	4.399	4.399	4.399	4.399	1.303	.573	.924

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
1.64	3.915	0.000	66.7	0.0						
1.92	3.927	0.000	73.2	60.1	0.0					
2.25	3.925	0.000	75.9	68.6	39.9	0.0				
2.47	3.923	0.000	77.8	70.3	43.7	57.4	0.0			
6.85	3.905	0.000	97.9	91.9	69.6	93.7	91.1	0.0		
9.35	3.892	0.000	103.4	98.1	75.7	101.3	99.5	82.6	0.0	
15.45	3.917	0.000	111.7	106.3	84.5	110.9	110.4	105.3	73.4	0.0
20.00	3.940	0.000	114.8	110.5	88.5	116.7	116.5	115.7	94.7	90.4
30.00	.757	0.000	44.8	55.9	44.3	90.1	99.3	119.5	109.8	109.8
40.00	-2.132	0.000	26.5	35.2	21.8	61.3	68.6	86.6	76.5	75.3
50.00	-.729	0.000	17.3	25.6	10.5	46.4	52.4	68.9	57.7	56.5
60.00	-.318	0.000	12.6	20.2	3.9	38.0	43.0	58.2	46.9	45.6
70.00	-.139	0.000	8.7	15.9	0.0	31.1	35.0	50.1	38.4	36.9
80.00	-.051	0.000	5.8	12.6	0.0	25.2	28.4	44.3	32.5	31.5
90.00	-.015	0.000	2.8	9.5	0.0	20.6	23.3	39.6	27.5	25.8
100.00	-.007	0.000	0.0	4.8	0.0	15.3	19.3	34.8	22.4	19.6
110.00	-.006	0.000	0.0	2.3	0.0	8.5	13.1	30.3	18.0	13.8
120.00	-.008	0.000	0.0	1.1	0.0	3.5	9.2	27.1	10.7	5.4
130.00	-.003	0.000	0.0	0.0	0.0	.5	5.2	18.2	4.5	0.0
138.60	0.000	0.000	0.0	0.0	0.0	0.0	3.3	15.9	0.0	0.0

INFLOW VOLUME = 51.29 MM M2/M/M
DRAINBACK VOLUME = 25.78 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.923 L/S
INFLOW TIME = 26.57 MIN
AVE. SLOPE = -.00005 M/M
AVE. TOP WIDTH A = 39.068
AVE. TOP WIDTH B = .539
AVE. WET PERIM A = 38.765
AVE. WET PERIM B = .549
AVE. SHAPE PROF = .145
AVE. SHAPE DEPTH = .223
AVE. SHAPE ADVAN = 1.230

Table 33. Water surface profile data for Test Number 132, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 132

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	30	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	39.50	33.90	29.56	33.88	30.21	34.54	43.50	49.48	39.75	34.54	23.79	0.00
*****TOP WIDTH*******												
R^2	.975	.992	.977	.928	.956	.973	.986	.989	.983	.956	.978	.974
*TW=A(D)^B * A	9.590	9.976	4.412	7.032	6.258	23.212	7.338	9.392	17.484	49.390	23.522	13.284
TW & D, MM B	.824	.808	.974	.848	.908	.645	.863	.825	.704	.485	.635	.756
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	9.754	10.122	4.842	7.276	6.558	23.154	7.578	9.560	17.490	49.146	23.460	13.364
WP & D, MM B	.838	.823	.979	.867	.920	.656	.879	.839	.717	.493	.646	.770
SURF. SHAPE FACT.												
*PROFILE *	.138	.091	.080	.098	.082	.200	.298	.438	.376	.434	.297	.613
*DEPTH *	.224	.147	.130	.159	.134	.198	.276	.255	.280	.270	.242	.317
*ADVANCE *	1.624	1.624	1.624	1.624	1.624	.989	.928	.583	.745	.622	.816	.386

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
1.28	3.861	0.000	39.0	0.0										
1.97	3.886	0.000	59.7	70.3	0.0									
2.08	3.886	0.000	63.2	74.4	67.6	0.0								
3.87	3.886	0.000	77.6	94.3	90.5	77.1	0.0							
7.30	3.886	0.000	90.9	110.3	110.0	98.4	93.8	0.0						
11.00	3.886	0.000	98.8	118.2	117.5	107.3	105.6	77.4	0.0					
15.00	3.888	0.000	103.1	123.0	122.7	113.3	112.2	92.0	62.4	0.0				
22.00	3.905	0.000	108.4	128.3	128.2	119.8	119.7	105.1	85.6	65.0	0.0			
28.10	3.925	0.000	111.7	133.8	132.3	124.6	124.1	112.1	95.9	80.4	66.4	0.0		
36.00	3.949	0.000	116.2	135.9	136.0	129.1	128.2	118.3	100.1	87.2	83.5	68.2	0.0	
42.40	3.979	0.000	118.3	137.3	138.3	132.5	132.4	122.5	107.3	95.6	91.9	81.3	64.9	0.0
50.00	3.988	0.000	121.4	140.2	140.8	134.3	135.4	126.9	112.1	101.8	99.7	92.6	87.5	93.4
60.00	3.964	0.000	126.8	142.9	145.3	136.3	140.4	131.2	118.3	110.1	111.9	110.2	112.4	123.1
70.00	-2.040	0.000	48.6	73.1	83.4	85.4	98.0	108.5	103.5	104.3	112.7	115.2	119.6	129.4
80.00	-2.756	0.000	37.0	62.8	70.6	71.5	82.9	92.4	86.8	86.5	94.5	96.9	101.6	112.2
90.00	-1.704	0.000	28.0	54.2	61.4	61.2	72.1	80.1	73.5	72.8	80.5	83.1	87.6	97.5
100.00	-1.092	0.000	21.3	48.2	55.0	54.2	64.3	70.1	63.7	62.6	69.9	71.4	75.4	85.7
110.00	-.722	0.000	15.5	43.5	49.7	48.3	57.4	62.8	55.3	53.7	60.8	62.8	67.6	77.3
120.00	-.470	0.000	9.9	39.3	45.2	42.5	51.1	55.2	47.2	44.8	51.1	54.1	57.3	69.1
130.00	-.288	0.000	5.6	36.3	41.4	37.8	45.8	49.3	41.6	40.3	46.8	49.5	54.3	61.9
140.00	-.162	0.000	1.2	32.8	37.5	33.4	41.1	44.0	34.9	32.6	39.6	41.4	45.3	54.3
150.00	-.078	0.000	0.0	29.6	33.6	29.0	37.1	39.7	30.7	27.7	35.4	36.6	39.7	50.1
160.00	-.030	0.000	0.0	24.3	28.8	24.0	33.3	35.6	25.3	22.0	28.9	30.0	32.8	42.5
170.00	-.017	0.000	0.0	15.7	22.0	17.6	29.1	31.1	20.4	16.2	22.0	22.8	24.9	35.4
180.00	-.013	0.000	0.0	5.5	14.7	12.0	24.7	27.2	16.5	10.8	17.0	16.1	16.6	28.3
190.00	-.011	0.000	0.0	0.0	8.0	6.8	21.6	23.9	11.7	3.2	10.2	10.2	8.2	21.3
200.00	-.003	0.000	0.0	0.0	0.0	1.0	16.9	19.0	5.8	0.0	2.9	1.4	0.0	10.8
210.00	0.000	0.000	0.0	0.0	0.0	0.0	11.3	12.4	.3	0.0	0.0	0.0	0.0	0.0
219.00	0.000	0.000	0.0	0.0	0.0	0.0	6.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 61.30 MM M2/M/M
DRAINBACK VOLUME = 26.28 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.936 L/S
INFLOW TIME = 63.28 MIN
AVE. SLOPE = -.00007 M/M
AVE. TOP WIDTH A = 12.673
AVE. TOP WIDTH B = .760
AVE. WET PERIM A = 12.731
AVE. WET PERIM B = .776
AVE. SHAPE PROF = .230
AVE. SHAPE DEPTH = .219
AVE. SHAPE ADVAN = 1.027

Table 34. Water surface profile data for Test Number 133, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 133

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	39	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.27	28.41	12.31	3.84	7.88	41.03	19.03	42.70	40.78	15.03	18.42	6.42	12.84	13.17	19.92	0.00
*****TOP WIDTH*******																
R^2	.891	.844	.975	.972	.988	.917	.876	.977	.974	.997	.978	.939	.946	.985	.978	.985
*TW=A(D)^B * A	104.988	107.560	44.840	35.316	32.664	42.030	30.592	22.302	33.350	25.360	25.612	4.174	17.958	37.104	22.844	37.772
TW & D, MM B	.361	.346	.523	.557	.586	.548	.596	.667	.597	.634	.637	.973	.716	.556	.650	.543
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	104.768	107.276	44.712	35.198	32.580	41.930	30.516	22.294	33.302	25.320	25.574	4.628	18.002	36.974	22.802	37.606
WP & D, MM B	.365	.350	.530	.565	.594	.554	.604	.676	.604	.643	.646	.979	.726	.565	.661	.552
SURF. SHAPE FACT.																
*PROFILE *	.152	.051	.034	.034	.046	.052	.148	.275	.505	.586	.516	.397	.387	.315	.280	0.000
*DEPTH *	.494	.165	.111	.111	.150	.075	.179	.190	.312	.337	.372	.293	.255	.218	.419	.437
*ADVANCE *	3.247	3.247	3.247	3.247	3.247	1.438	1.206	.631	.617	.677	.720	.753	.659	.632	1.495	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
2.05	3.981	0.000	43.4	0.0														
2.54	3.997	0.000	51.0	45.8	0.0													
3.14	3.997	0.000	60.4	58.8	68.2	0.0												
3.56	3.997	0.000	66.9	65.3	78.0	71.0	0.0											
9.52	3.997	0.000	89.0	85.6	95.2	98.5	89.8	0.0										
12.62	3.997	0.000	92.3	92.7	93.2	105.2	96.8	65.8	0.0									
16.02	3.997	0.000	95.7	94.4	103.4	110.7	102.3	74.2	66.3	0.0								
22.12	3.994	0.000	101.4	98.5	109.7	104.8	100.5	75.5	84.0	52.2	0.0							
29.72	3.978	0.000	108.2	103.9	118.0	117.7	110.3	84.4	93.8	60.8	42.8	0.0						
37.32	3.957	0.000	114.8	110.6	125.7	126.1	119.3	94.2	104.3	73.3	57.6	58.8	0.0					
44.92	3.942	0.000	119.1	114.8	130.1	130.9	124.0	100.1	111.2	81.9	69.4	77.3	53.7	0.0				
52.52	3.941	0.000	122.0	117.8	132.9	133.9	127.3	103.8	115.8	87.9	76.8	88.6	71.6	71.3	0.0			
61.62	3.941	0.000	124.9	120.7	135.7	136.8	130.2	107.1	119.7	92.4	83.2	97.1	85.2	90.6	72.9	0.0		
70.72	3.941	0.000	127.1	123.7	137.8	138.5	132.0	109.5	123.1	96.8	88.5	104.6	93.9	100.9	86.9	66.6	0.0	
74.12	3.941	0.000	127.3	124.4	138.5	139.0	132.6	110.2	123.7	97.7	89.7	106.1	95.5	102.8	88.5	71.7	41.3	0.0
80.00	3.941	0.000	128.5	125.5	139.6	140.2	133.8	111.2	125.1	100.0	92.7	109.4	98.9	106.8	93.1	80.2	61.0	73.5
90.00	3.941	0.000	130.0	126.9	141.2	141.9	135.7	113.5	127.5	103.4	96.9	114.1	106.3	115.9	106.4	100.5	91.7	114.9
100.00	3.941	0.000	132.4	129.3	142.9	143.8	137.4	115.6	130.8	106.8	101.7	121.5	115.5	126.9	120.4	117.5	111.8	133.9
110.00	-1.472	0.000	49.5	59.5	90.3	91.4	99.4	87.8	111.8	95.0	97.7	122.7	118.6	131.2	127.2	126.5	119.6	141.9
120.00	-3.054	0.000	29.3	38.2	63.0	72.6	73.3	67.4	95.2	82.1	84.4	108.6	106.4	120.4	116.2	116.8	111.4	132.5
130.00	-1.894	0.000	22.7	32.3	56.3	64.9	64.7	58.1	84.5	71.4	73.4	98.2	94.3	107.9	103.7	103.3	97.8	118.3
140.00	-1.326	0.000	17.5	27.4	50.9	58.0	57.7	50.0	76.0	62.0	63.9	88.5	85.7	99.7	96.2	96.1	89.2	110.7
150.00	-.913	0.000	13.6	23.8	46.4	52.4	51.2	42.3	68.2	53.3	54.9	78.7	76.4	90.3	85.7	85.6	80.1	101.0
160.00	-.641	0.000	10.7	20.8	42.4	47.6	45.4	35.5	61.2	46.8	48.2	70.8	68.5	82.5	78.3	77.8	72.0	92.8
170.00	-.441	0.000	8.0	17.7	39.0	43.2	40.4	29.1	56.5	40.3	41.0	65.2	61.8	75.6	71.1	70.9	64.8	86.0
180.00	-.278	0.000	5.2	14.9	35.7	39.2	35.6	22.9	52.3	35.7	36.3	60.1	56.0	69.6	64.7	64.2	57.7	78.0
190.00	-.158	0.000	2.1	12.3	32.5	35.0	30.5	15.8	47.4	30.1	30.4	53.8	50.9	64.8	60.9	60.3	53.1	74.1
200.00	-.077	0.000	0.0	9.6	29.6	31.2	26.2	9.8	43.4	25.4	24.4	48.4	45.7	59.2	54.1	53.1	47.9	68.7
210.00	-.028	0.000	0.0	6.3	26.6	28.2	22.7	4.8	39.7	21.7	21.2	44.5	41.5	54.9	50.4	49.9	42.7	64.3
220.00	-.011	0.000	0.0	1.7	23.1	25.2	19.7	0.0	35.4	16.8	15.7	38.7	35.0	47.6	41.9	40.5	34.9	55.1
230.00	-.007	0.000	0.0	0.0	20.7	21.7	16.5	0.0	31.7	10.9	11.0	32.7	30.3	43.4	38.2	35.4	28.1	49.2
240.00	-.007	0.000	0.0	0.0	17.4	19.0	13.8	0.0	27.6	7.6	7.3	28.9	25.2	38.9	34.2	28.1	19.9	41.4
250.00	-.009	0.000	0.0	0.0	13.6	16.2	10.7	0.0	23.1	1.9	2.2	23.3	19.9	33.1	28.6	19.4	9.1	32.8
260.00	-.011	0.000	0.0	0.0	9.1	12.7	7.8	0.0	16.1	0.0	0.0	15.4	14.0	27.5	22.9	9.1	0.0	24.1
270.00	-.011	0.000	0.0	0.0	5.3	9.7	5.6	0.0	10.9	0.0	0.0	8.6	7.6	21.0	17.2	0.0	0.0	15.9
280.00	-.009	0.000	0.0	0.0	1.2	5.9	2.6	0.0	5.7	0.0	0.0	1.7	2.1	14.3	12.3	0.0	0.0	9.7
290.00	-.006	0.000	0.0	0.0	0.0	1.9	.2	0.0	0.0	0.0	0.0	0.0	0.0	4.4	3.9	0.0	0.0	1.9
295.80	-.005	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.2	.4	0.0	0.0	0.0

INFLOW VOLUME = 69.24 MM M2/M/M
DRAINBACK VOLUME = 20.55 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.956 L/S
INFLOW TIME = 104.92 MIN
AVE. SLOPE = -.00003 M/M
AVE. TOP WIDTH A = 33.790
AVE. TOP WIDTH B = .578
AVE. WET PERIM A = 33.517
AVE. WET PERIM B = .588
AVE. SHAPE PROF = .252
AVE. SHAPE DEPTH = .261
AVE. SHAPE ADVAN = 1.030

Table 35. Water surface profile data for Test Number 134, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 134

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	20	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		21.79	19.71	19.64	10.76	10.15	0.00	13.50	15.87
*****TOP WIDTH*******									
	R^2	.990	.984	.984	.992	.943	.953	.963	.991
*TW=A(D)^B *	A	53.300	72.452	40.224	19.202	33.318	50.788	45.340	19.080
TW & D, MM	B	.489	.411	.542	.684	.552	.479	.516	.683
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	53.102	72.168	40.048	19.182	33.100	50.462	45.128	19.066
WP & D, MM	B	.495	.417	.550	.696	.564	.488	.523	.695
SURF. SHAPE FACT.									
*PROFILE	*	.457	.538	.895	.525	.345	.239	.807	.275
*DEPTH	*	.212	.250	.416	.244	.160	.229	.414	.287
*ADVANCE	*	.465	.465	.465	.465	.465	.958	.513	.691

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.07	3.372	0.000	3.1	0.0						
.31	3.832	0.000	13.8	11.5	0.0					
1.36	3.837	0.000	61.3	51.2	27.9	0.0				
3.26	3.847	0.000	79.1	72.0	46.9	64.1	0.0			
5.32	3.861	0.000	88.9	82.8	59.4	81.1	77.2	0.0		
8.12	3.878	0.000	96.2	90.8	68.0	92.7	89.7	76.5	0.0	
14.22	3.886	0.000	105.8	100.1	77.9	103.6	101.7	99.8	69.4	0.0
20.00	3.900	0.000	113.7	107.5	85.0	111.2	109.9	115.0	98.2	94.7
30.00	-.340	0.000	37.0	46.8	33.0	74.6	82.4	107.1	96.5	95.3
40.00	-1.508	0.000	21.3	29.7	14.6	50.6	56.0	77.9	67.4	66.0
50.00	-.512	0.000	14.4	22.4	5.7	38.6	42.7	62.6	51.7	50.1
60.00	-.200	0.000	9.2	16.4	0.0	29.6	32.7	52.0	40.0	38.1
70.00	-.071	0.000	6.0	13.1	0.0	24.1	26.2	45.6	33.0	31.3
80.00	-.018	0.000	1.7	8.4	0.0	18.7	20.8	39.6	27.1	24.7
90.00	-.007	0.000	0.0	2.6	0.0	12.4	15.4	33.1	21.0	18.9
100.00	-.006	0.000	0.0	0.0	0.0	6.6	10.2	27.1	14.3	11.4
110.00	-.005	0.000	0.0	0.0	0.0	1.5	5.6	22.5	8.9	5.7
120.00	-.004	0.000	0.0	0.0	0.0	0.0	.2	16.0	1.9	1.2
122.40	0.000	0.000	0.0	0.0	0.0	0.0	0.0	11.7	.5	.4

INFLOW VOLUME = 47.09 MM M2/M/M
DRAINBACK VOLUME = 22.07 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.887 L/S
INFLOW TIME = 24.62 MIN
AVE. SLOPE = -.00005 M/M
AVE. TOP WIDTH A = 39.068
AVE. TOP WIDTH B = .539
AVE. WET PERIM A = 38.765
AVE. WET PERIM B = .549
AVE. SHAPE PROF = .544
AVE. SHAPE DEPTH = .277
AVE. SHAPE ADVAN = .601

Table 36. Water surface profile data for Test Number 135, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 135

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	30	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	39.50	33.90	29.56	33.88	30.21	34.54	43.50	49.48	39.75	34.54	23.79	0.00
*****TOP WIDTH*******												
R^2	.975	.992	.977	.928	.956	.973	.986	.989	.983	.956	.978	.974
*TW=A(D)^B * A	9.590	9.976	4.412	7.032	6.258	23.212	7.338	9.392	17.484	49.390	23.522	13.284
TW & D, MM B	.824	.808	.974	.848	.908	.645	.863	.825	.704	.485	.635	.756
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	9.754	10.122	4.842	7.276	6.558	23.154	7.578	9.560	17.490	49.146	23.460	13.364
WP & D, MM B	.838	.823	.979	.867	.920	.656	.879	.839	.717	.493	.646	.770
SURF. SHAPE FACT.												
*PROFILE *	.253	.204	.191	.195	.175	.163	.206	.349	.515	.610	.593	0.000
*DEPTH *	.212	.171	.160	.163	.147	.162	.191	.257	.455	.401	.421	.565
*ADVANCE *	.840	.840	.840	.840	.840	.994	.926	.737	.883	.657	.703	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.34	3.845	0.000	16.8	0.0										
.77	3.942	0.000	38.3	45.2	0.0									
1.31	3.944	0.000	57.9	73.4	68.1	0.0								
2.86	3.947	0.000	67.4	83.7	81.6	66.4	0.0							
6.75	3.954	0.000	82.6	101.5	101.8	93.1	88.9	0.0						
10.15	3.964	0.000	90.4	109.6	109.8	101.6	99.5	74.0	0.0					
13.85	3.974	0.000	95.8	114.6	115.0	107.7	105.6	86.2	61.8	0.0				
18.75	3.986	0.000	97.7	118.7	119.4	110.6	111.8	94.1	74.0	54.9	0.0			
23.05	3.996	0.000	104.7	123.8	124.4	118.4	117.2	104.3	87.0	66.8	45.4	0.0		
29.15	3.997	0.000	108.6	127.7	128.5	121.9	122.4	110.3	94.6	77.0	69.1	50.2	0.0	
35.25	3.997	0.000	112.3	131.5	132.1	126.0	126.3	116.6	102.3	86.0	81.6	68.2	47.7	0.0
40.00	3.997	0.000	114.4	133.5	134.1	128.0	128.7	118.3	104.8	90.7	87.4	77.4	63.6	55.4
50.00	3.997	0.000	117.6	137.1	138.1	131.9	132.8	124.3	110.7	97.9	98.1	93.9	94.5	105.0
60.00	1.768	0.000	61.7	88.3	95.1	99.0	108.3	118.5	111.2	103.4	107.0	106.6	114.5	125.0
70.00	-2.957	0.000	37.3	62.3	69.1	70.4	82.3	91.7	89.2	85.7	93.2	95.9	102.4	113.7
80.00	-1.526	0.000	29.0	53.8	60.2	60.1	70.9	78.9	75.7	71.6	77.7	79.6	88.3	95.4
90.00	-.093	0.000	21.1	46.3	52.6	51.6	62.1	67.5	62.6	58.3	65.1	66.7	73.7	80.7
100.00	-.565	0.000	14.6	41.6	47.2	45.5	54.9	58.7	54.3	49.4	56.0	57.7	61.5	72.6
110.00	-.319	0.000	8.1	37.1	42.1	39.8	48.1	51.4	46.4	40.6	47.6	49.8	54.1	65.1
120.00	-.162	0.000	2.9	34.0	38.4	34.9	42.7	45.7	40.0	34.2	41.9	43.2	47.0	57.3
130.00	-.071	0.000	0.0	30.3	33.6	29.5	37.5	40.1	33.4	26.9	34.6	36.2	39.9	50.7
140.00	-.023	0.000	0.0	25.0	28.3	24.1	33.4	35.1	28.7	21.4	28.3	29.4	33.3	43.9
150.00	-.010	0.000	0.0	17.0	21.4	17.6	28.5	31.7	23.8	16.3	22.0	22.3	25.1	35.6
160.00	-.006	0.000	0.0	7.5	13.5	10.8	23.9	27.1	18.4	10.5	15.5	14.9	15.8	27.6
170.00	-.006	0.000	0.0	0.0	5.5	4.3	19.0	21.8	12.3	1.8	8.5	6.6	5.4	19.2
180.00	-.004	0.000	0.0	0.0	0.0	0.0	14.6	17.3	6.0	0.0	3.0	0.0	0.0	10.6
190.00	-.003	0.000	0.0	0.0	0.0	0.0	7.8	9.5	0.0	0.0	0.0	0.0	0.0	0.0
200.00	-.002	0.000	0.0	0.0	0.0	0.0	.4	1.4	0.0	0.0	0.0	0.0	0.0	0.0
202.80	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 56.90 MM M2/M/M
DRAINBACK VOLUME = 19.64 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.987 L/S
INFLOW TIME = 58.00 MIN
AVE. SLOPE = -.00007 M/M
AVE. TOP WIDTH A = 12.673
AVE. TOP WIDTH B = .760
AVE. WET PERIM A = 12.731
AVE. WET PERIM B = .776
AVE. SHAPE PROF = .315
AVE. SHAPE DEPTH = .275
AVE. SHAPE ADVAN = .828

Table 37. Water surface profile data for Test Number 136, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 136

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	36	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM		32.27	38.41	22.31	13.84	17.88	51.03	29.03	52.70	50.78	25.03	18.67	6.42	12.84	13.17	13.92	0.00
*****TOP WIDTH********																	
	R^2	.891	.844	.975	.972	.988	.917	.876	.977	.974	.987	.978	.939	.946	.985	.978	.985
*TW=A(D)^B *	A	104.988	107.560	44.840	35.316	32.664	42.030	30.592	22.302	33.350	25.360	25.612	4.174	17.968	37.104	22.844	37.772
TW & D, MM	B	.361	.346	.523	.557	.586	.548	.596	.667	.597	.634	.637	.973	.716	.555	.650	.543
*****WETTED PER******																	
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	104.768	107.276	44.712	35.198	32.580	41.930	30.516	22.294	33.302	25.320	25.574	4.628	18.002	36.974	22.802	37.606
WP & D, MM	B	.365	.350	.530	.565	.594	.554	.604	.676	.604	.643	.646	.979	.726	.565	.661	.552
SURF. SHAPE FACT.																	
*PROFILE	*	.380	.402	.360	.334	.344	.346	.604	.003	.548	.558	.488	.625	.416	.633	.332	0.000
*DEPTH	*	.234	.248	.222	.206	.212	.285	.261	.113	.456	.400	.364	.301	.363	.439	.433	.526
*ADVANCE	*	.616	.616	.616	.616	.616	.821	.433	44.649	.833	.705	.745	.482	.871	.693	1.304	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.20	3.773	0.000	4.2	0.0														
.60	3.941	0.000	13.1	9.0	0.0													
1.85	3.941	0.000	40.3	34.8	38.7	0.0												
2.87	3.941	0.000	62.4	55.8	63.6	56.8	0.0											
6.27	3.941	0.000	78.0	72.8	85.0	81.7	69.1	0.0										
10.27	3.941	0.000	87.9	83.8	97.5	95.4	87.3	47.4	0.0									
19.96	3.941	0.000	102.2	98.1	112.6	112.7	104.8	68.2	84.4	0.0								
20.06	3.941	0.000	102.3	98.2	112.7	112.8	105.0	68.3	84.7	0.0	0.0							
24.97	3.941	0.000	106.1	102.3	117.2	117.6	110.2	74.3	94.0	60.1	38.0	0.0						
31.07	3.941	0.000	110.5	107.0	121.8	122.2	115.0	80.4	101.2	69.8	53.1	41.9	0.0					
37.17	3.941	0.000	113.1	109.4	124.2	124.9	117.9	83.9	105.4	75.4	61.5	56.9	40.1	0.0				
47.46	3.955	0.000	116.3	112.2	127.7	128.5	121.3	87.7	108.3	79.7	69.4	71.4	62.3	66.7	0.0			
53.56	3.974	0.000	117.4	114.0	129.5	129.5	123.2	89.6	111.9	84.0	73.9	77.2	72.8	79.2	48.8	0.0		
61.47	3.989	0.000	119.2	115.7	130.6	131.7	124.4	91.7	114.4	86.8	78.1	83.4	82.0	89.4	65.0	52.5	0.0	
64.87	3.997	0.000	119.9	116.3	131.6	132.4	125.7	93.2	116.0	88.5	80.0	85.8	84.8	92.9	68.9	61.3	35.7	0.0
70.00	3.934	0.000	121.6	117.9	133.0	133.6	127.3	94.0	116.4	90.6	82.9	89.1	88.5	97.6	74.7	71.0	52.1	57.4
80.00	3.980	0.000	123.4	120.0	134.8	136.0	129.2	96.8	119.8	93.6	87.1	94.4	95.6	105.1	84.6	87.8	78.7	101.1
90.00	3.961	0.000	125.0	121.7	138.0	138.6	131.2	93.9	123.8	99.4	93.4	101.5	105.0	114.8	96.2	102.9	95.9	119.2
100.00	-.393	0.000	46.5	51.4	73.9	93.2	94.6	73.4	105.1	89.2	89.4	101.1	107.1	118.9	103.9	113.3	108.6	130.8
110.00	-2.862	0.000	26.3	37.3	57.6	66.1	65.4	48.9	85.6	71.9	74.4	89.3	97.9	110.1	95.2	105.7	101.3	122.3
120.00	-1.526	0.000	19.8	28.2	51.7	57.6	56.5	39.5	75.0	61.1	63.3	77.4	84.7	98.3	84.2	95.1	89.2	110.7
130.00	-.992	0.000	15.6	24.3	46.2	51.1	49.2	29.5	65.0	51.1	51.6	65.8	71.8	86.3	71.8	81.8	76.4	97.5
140.00	-.652	0.000	11.9	22.5	42.0	46.2	42.8	22.8	59.2	44.5	44.2	57.8	62.9	78.5	64.1	73.7	66.7	88.7
150.00	-.405	0.000	8.4	18.5	37.7	40.5	36.4	14.4	51.9	35.3	36.2	50.0	55.5	69.6	53.6	62.6	56.3	77.6
160.00	-.223	0.000	4.9	15.8	33.9	36.3	31.4	7.6	48.0	28.4	29.7	43.0	49.5	62.5	46.5	55.9	49.6	71.2
170.00	-.103	0.000	2.3	12.8	30.1	31.9	26.6	0.0	43.7	25.7	24.9	37.3	44.2	57.4	42.4	51.4	44.4	66.6
180.00	-.029	0.000	0.0	10.0	26.6	28.3	22.8	0.0	38.2	20.0	18.1	30.4	37.4	49.8	33.9	42.7	36.4	57.9
190.00	-.010	0.000	0.0	5.2	22.4	24.0	18.3	0.0	31.5	12.1	10.2	23.1	29.5	43.1	27.3	35.5	28.7	50.3
200.00	-.007	0.000	0.0	.0	19.0	21.0	15.3	0.0	27.6	8.3	5.8	17.5	23.6	37.2	21.9	28.4	20.6	42.3
210.00	-.006	0.000	0.0	0.0	13.8	16.1	10.8	0.0	22.3	3.4	1.3	9.9	16.9	30.9	16.1	19.6	10.5	33.7
220.00	-.005	0.000	0.0	0.0	8.7	11.8	7.8	0.0	17.8	0.0	0.0	2.0	10.3	22.2	8.2	7.8	.1	23.3
230.00	-.005	0.000	0.0	0.0	3.5	7.9	4.8	0.0	11.4	0.0	0.0	0.0	4.2	13.2	2.6	0.0	0.0	15.0
240.00	-.004	0.000	0.0	0.0	0.0	3.0	1.2	0.0	3.8	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	7.8
250.00	-.004	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.2
250.80	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME	=	63.34 MM M2/M/M
DRAINBACK VOLUME	=	15.94 MM M2/M/M
RUNOFF VOLUME	=	0.00 MM M2/M/M
AVE. INFLOW RATE	=	3.960 L/S
INFLOW TIME	=	95.88 MIN
AVE. SLOPE	=	-.00007 M/M
AVE. TOP WIDTH A	=	33.790
AVE. TOP WIDTH B	=	.578
AVE. WET PERIM A	=	33.517
AVE. WET PERIM B	=	.588
AVE. SHAPE PROF	=	.425
AVE. SHAPE DEPTH	=	.316
AVE. SHAPE ADVAN	=	.754

Table 38. Water surface profile data for Test Number 137, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 137

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	14	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		0.00	18.18	15.61	6.24	5.39	31.54	21.13	28.33
*****TOP WIDTH*******									
	R^2	.987	.943	.972	.977	.969	.959	.951	.836
*TW=A(D)^B *	A	13.080	64.516	28.106	31.236	19.702	2.508	12.774	32.812
TW & D, MM	B	.771	.441	.615	.580	.683	1.043	.775	.574
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	13.180	64.250	28.048	31.096	19.696	3.204	12.870	32.640
WP & D, MM	B	.783	.447	.624	.590	.694	1.028	.788	.585
SURF. SHAPE FACT.									
*PROFILE	*	.186	.327	.377	.535	.362	1.000	.466	.003
*DEPTH	*	.107	.188	.216	.307	.208	.495	.244	1.000
*ADVANCE	*	.573	.573	.573	.573	.573	.446	.522	44.649

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.07	3.487	0.000	3.7	0.0						
.22	3.997	0.000	12.5	8.4	0.0					
.74	3.997	0.000	41.8	28.2	25.8	0.0				
2.03	3.997	0.000	94.4	68.0	65.4	57.3	0.0			
5.13	3.997	0.000	104.8	81.8	81.4	83.7	82.3	0.0		
12.73	3.997	0.000	119.4	96.9	98.1	104.0	104.5	57.6	0.0	
22.09	3.997	0.000	128.1	106.0	107.7	114.2	115.3	77.9	76.0	0.0
30.00	3.997	0.000	108.9	92.9	99.4	110.8	114.7	89.5	102.7	94.1
40.00	-2.055	0.000	40.7	31.8	41.9	56.3	63.3	50.0	70.5	62.5
50.00	-.459	0.000	23.4	14.9	25.0	35.7	39.8	22.9	41.9	33.6
60.00	-.055	0.000	8.3	0.0	7.3	17.5	21.4	2.7	21.0	13.9
70.00	-.006	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
70.80	-.005	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 60.44 MM M2/M/M
DRAINBACK VOLUME = 14.12 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.996 L/S
INFLOW TIME = 30.73 MIN
AVE. SLOPE = .00018 M/M
AVE. TOP WIDTH A = 21.375
AVE. TOP WIDTH B = .659
AVE. WET PERIM A = 21.296
AVE. WET PERIM B = .672
AVE. SHAPE PROF = .465
AVE. SHAPE DEPTH = .345
AVE. SHAPE ADVAN = .546

Table 39. Water surface profile data for Test Number 138, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 138

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	19	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	30.35	31.51	19.42	32.99	34.33	34.45	48.75	48.36	42.25	26.95	49.45	0.00
*****TOP WIDTH*******												
R^2	.928	.990	.954	.973	.979	.989	.958	.938	.976	.957	.962	.982
*TW=A(D)^B * A	52.628	22.934	30.502	24.262	15.442	11.580	27.590	24.922	18.152	39.844	20.352	10.470
TW & D, MM B	.506	.660	.587	.640	.722	.787	.599	.621	.693	.535	.666	.799
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	52.404	22.895	30.386	24.208	15.470	11.692	27.460	24.810	18.144	39.652	20.302	10.602
WP & D, MM B	.512	.671	.597	.650	.736	.801	.610	.634	.705	.544	.679	.814
SURF. SHAPE FACT.												
*PROFILE *	.195	.140	.124	.132	.129	.171	.149	.433	.448	.335	.745	0.000
*DEPTH *	.215	.154	.136	.145	.142	.140	.154	.205	.203	.212	.536	.729
*ADVANCE *	1.098	1.098	1.098	1.098	1.098	.822	1.031	.473	.454	.634	.720	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.89	4.071	0.000	26.2	0.0										
1.67	4.110	0.000	49.2	48.7	0.0									
2.82	4.110	0.000	77.4	82.1	85.3	0.0								
4.54	4.110	0.000	89.1	91.8	99.8	75.9	0.0							
11.42	4.110	0.000	103.7	109.3	119.5	103.2	97.9	0.0						
18.70	4.110	0.000	110.5	116.0	126.5	111.2	107.2	90.1	0.0					
24.72	4.110	0.000	112.4	117.8	130.0	112.8	111.1	96.8	76.4	0.0				
39.62	4.110	0.000	121.4	123.6	135.1	120.8	118.8	110.0	92.8	75.5	0.0			
59.22	4.110	0.000	125.1	128.0	139.3	125.2	123.3	116.4	102.6	88.7	78.1	0.0		
75.52	4.110	0.000	127.7	130.5	141.7	128.3	126.7	121.0	108.1	95.4	87.1	73.3	0.0	
90.92	4.110	0.000	129.1	132.4	143.8	130.3	128.9	123.7	110.8	98.2	91.5	82.6	36.2	0.0
100.00	4.110	0.000	130.3	133.2	144.8	131.0	129.7	125.1	112.2	100.3	94.3	86.7	42.4	59.6
110.00	4.110	0.000	132.6	128.7	146.4	131.2	130.0	125.8	114.5	102.2	95.6	91.6	53.2	80.8
120.00	-1.902	0.000	18.0	42.1	66.2	63.3	71.4	83.6	84.0	82.7	84.1	91.6	60.1	91.3
130.00	-.765	0.000	4.6	23.9	43.3	36.5	44.3	56.4	54.5	53.3	59.4	66.9	37.3	68.6
140.00	-.099	0.000	0.0	8.3	25.4	16.3	21.4	33.0	30.1	26.5	31.0	40.1	10.5	41.8
150.00	-.008	0.000	0.0	0.0	3.0	0.0	0.0	8.5	2.5	0.0	1.5	5.5	0.0	6.6
151.20	0.000	0.000	0.0	0.0	.5	0.0	0.0	5.6	0.0	0.0	0.0	1.5	0.0	3.1

INFLOW VOLUME = 114.19 MM M2/M/M
DRAINBACK VOLUME = 9.77 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.110 L/S
INFLOW TIME = 112.92 MIN
AVE. SLOPE = -.00001 M/M
AVE. TOP WIDTH A = 23.299
AVE. TOP WIDTH B = .644
AVE. WET PERIM A = 23.159
AVE. WET PERIM B = .657
AVE. SHAPE PROF = .273
AVE. SHAPE DEPTH = .248
AVE. SHAPE ADVAN = .810

Table 40. Water surface profile data for Test Number 139, Table 1.

WMC FURROW DRAINBACK STUDY NUMBER 139

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	25	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.21	21.10	17.25	3.04	9.58	0.00	6.07	35.96	14.32	19.50	20.42	24.48	23.12	12.23	8.42	20.98
*****TOP WIDTH*******																
R^2	.970	.851	.934	.956	.961	.987	.964	.946	.987	.992	.972	.985	.981	.957	.979	.981
*TW=A(D)^B * A	36.904	98.484	73.432	9.520	16.950	19.278	8.694	22.086	26.366	26.004	26.496	19.846	24.688	53.438	23.356	11.460
TW & D, MM B	.556	.337	.392	.832	.730	.681	.838	.632	.623	.619	.617	.680	.625	.468	.642	.801
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	36.830	98.232	73.226	9.702	17.006	19.254	8.884	21.982	26.232	25.902	26.426	19.828	24.606	53.144	23.284	11.596
WP & D, MM B	.563	.341	.398	.844	.740	.693	.853	.646	.633	.630	.627	.692	.637	.476	.653	.812
SURF. SHAPE FACT.																
*PROFILE *	.268	.110	.148	.134	.117	.133	.422	.240	.447	.329	.666	.563	1.000	.195	.163	0.000
*DEPTH *	.273	.112	.151	.136	.119	.113	.231	.221	.293	.248	.389	.334	.390	.122	.207	.504
*ADVANCE *	1.019	1.019	1.019	1.019	1.019	.849	.548	.922	.655	.754	.584	.699	.357	.626	1.266	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.66	3.947	0.000	41.6	0.0														
1.31	3.997	0.000	48.7	49.6	0.0													
2.58	3.997	0.000	62.8	60.8	44.3	0.0												
3.84	3.997	0.000	76.7	71.9	73.5	74.7	0.0											
8.17	3.997	0.000	85.3	82.4	86.0	91.7	74.1	0.0										
13.17	3.937	0.000	91.4	88.3	92.7	93.9	85.1	96.2	0.0									
22.27	3.997	0.000	99.3	96.2	101.2	109.8	96.4	110.2	87.1	0.0								
28.37	3.997	0.000	102.2	99.4	104.8	113.8	101.1	116.8	100.0	54.9	0.0							
37.47	3.997	0.000	106.1	103.5	109.2	118.6	106.1	123.7	109.4	71.3	60.0	0.0						
45.96	3.997	0.000	108.0	105.5	111.5	120.9	108.7	127.3	114.2	79.0	75.7	49.5	0.0					
57.76	3.997	0.000	110.6	108.1	114.0	123.4	111.2	130.6	118.6	84.6	85.5	66.6	60.4	0.0				
68.37	3.989	0.000	112.7	110.7	115.9	125.7	113.9	133.8	122.1	89.5	90.3	74.7	68.7	52.3	0.0			
91.87	3.957	0.000	114.9	112.8	118.9	128.8	116.9	137.7	128.0	97.0	99.5	86.8	83.8	71.4	68.8	0.0		
106.97	3.967	0.000	116.0	114.1	120.1	130.0	118.2	139.3	129.9	99.4	101.0	90.9	88.1	76.5	76.5	59.7	0.0	
113.07	3.990	0.000	116.3	114.3	120.7	130.7	118.8	139.8	130.3	99.4	104.1	92.3	90.3	79.4	78.9	64.2	40.1	0.0
120.00	3.997	0.000	116.7	114.9	120.9	130.7	119.1	140.5	131.2	100.9	105.2	93.4	91.5	80.5	80.0	68.0	50.2	34.2
130.00	3.997	0.000	117.1	115.2	121.3	131.1	119.3	140.3	130.9	100.9	106.2	94.1	91.6	80.8	81.4	74.4	63.5	53.0
140.00	3.997	0.000	117.3	116.2	121.9	130.8	120.2	141.5	131.7	101.1	106.3	95.5	93.5	83.1	85.2	83.5	76.8	66.5
150.00	-.495	0.000	29.9	40.0	67.4	80.6	78.9	110.1	109.2	88.0	97.2	91.4	92.4	85.7	87.8	90.4	86.4	76.8
160.00	-1.349	0.000	11.0	22.9	44.3	59.0	51.4	83.0	83.4	61.7	76.4	72.2	76.1	72.3	80.0	87.7	85.0	75.8
170.00	-.424	0.000	1.9	14.6	33.9	46.8	38.3	67.5	66.8	45.6	57.7	53.3	57.9	54.8	63.3	74.4	71.0	60.8
180.00	-.118	0.000	0.0	6.5	25.2	37.1	27.6	55.4	53.0	30.7	41.8	37.5	41.6	37.9	46.4	56.4	52.7	42.0
190.00	-.020	0.000	0.0	0.0	13.0	25.2	15.8	43.7	40.0	18.4	24.7	19.3	25.0	22.4	30.6	36.1	33.3	24.2
200.00	-.008	0.000	0.0	0.0	0.0	13.7	3.1	31.4	26.2	3.5	5.7	0.0	3.4	0.0	11.1	11.7	8.7	2.5
208.20	0.000	0.000	0.0	0.0	0.0	2.9	0.0	12.6	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 96.15 MM M2/M/M
DRAINBACK VOLUME = 7.09 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.986 L/S
INFLOW TIME = 144.58 MIN
AVE. SLOPE = .00001 M/M
AVE. TOP WIDTH A = 25.791
AVE. TOP WIDTH B = .621
AVE. WET PERIM A = 25.573
AVE. WET PERIM B = .634
AVE. SHAPE PROF = .329
AVE. SHAPE DEPTH = .244
AVE. SHAPE ADVAN = .808

Table 41. Water surface profile data for Test Number 140, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 140

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	20	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	0.00	18.18	15.61	6.24	5.39	31.54	21.13	28.33
*****TOP WIDTH*******								
R^2	.987	.943	.972	.977	.969	.959	.951	.836
*TW=A(D)^B * A	13.080	64.516	28.106	31.236	19.702	2.508	12.774	32.812
TW & D, MM B	.771	.441	.615	.580	.683	1.043	.775	.574
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	13.180	64.250	28.048	31.096	19.696	3.204	12.870	32.640
WP & D, MM B	.783	.447	.624	.590	.694	1.028	.788	.585
SURF. SHAPE FACT.								
*PROFILE *	.396	.291	.856	.540	.371	.495	.555	.240
*DEPTH *	.166	.122	.358	.226	.155	.336	.367	.372
*ADVANCE *	.418	.418	.418	.418	.418	.678	.662	.922

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.03	2.983	0.000	1.4	0.0						
.12	3.941	0.000	4.8	39.2	0.0					
.94	3.937	0.000	37.7	49.2	28.7	0.0				
2.48	3.928	0.000	92.2	65.5	58.8	53.2	0.0			
5.25	3.912	0.000	105.8	80.5	80.1	82.0	82.7	0.0		
9.55	3.890	0.000	115.7	91.3	90.7	96.0	98.5	56.3	0.0	
14.75	3.886	0.000	123.4	99.7	99.4	105.3	108.3	73.2	70.3	0.0
20.00	3.886	0.000	129.1	104.7	104.4	111.5	116.3	85.5	96.5	87.4
30.00	.076	0.000	68.5	53.4	62.9	80.8	91.5	82.3	104.5	96.4
40.00	-2.090	0.000	45.7	32.2	39.8	54.2	62.9	50.0	69.8	61.7
50.00	-.724	0.000	33.2	21.2	28.5	40.2	48.2	33.3	53.3	45.1
60.00	-.293	0.000	25.6	14.3	21.1	31.8	38.9	21.5	40.8	32.7
70.00	-.115	0.000	21.5	10.1	17.4	27.0	33.6	14.9	34.3	26.2
80.00	-.040	0.000	17.0	5.5	13.2	22.6	28.8	9.1	28.0	20.3
90.00	-.014	0.000	13.8	0.0	8.7	17.5	23.6	3.1	20.6	12.5
100.00	-.010	0.000	10.4	0.0	4.6	13.7	20.1	0.0	15.1	7.5
110.00	-.009	0.000	1.9	0.0	0.0	7.2	15.0	0.0	6.8	2.4
120.00	-.007	0.000	0.0	0.0	0.0	0.0	8.3	0.0	0.0	0.0
129.60	0.000	0.000	0.0	0.0	0.0	0.0	.5	0.0	0.0	0.0

INFLOW VOLUME	=	48.82 MM M2/M/M
DRAINBACK VOLUME	=	26.38 MM M2/M/M
RUNOFF VOLUME	=	0.00 MM M2/M/M
AVE. INFLOW RATE	=	3.893 L/S
INFLOW TIME	=	25.48 MIN
AVE. SLOPE	=	.00018 M/M
AVE. TOP WIDTH A	=	21.375
AVE. TOP WIDTH B	=	.659
AVE. WET PERIM A	=	21.296
AVE. WET PERIM B	=	.672
AVE. SHAPE PROF	=	.500
AVE. SHAPE DEPTH	=	.263
AVE. SHAPE ADVAN	=	.506

Table 42. Water surface profile data for Test Number 141, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 141

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	27	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	30.35	34.01	19.42	32.99	34.33	34.45	48.75	47.86	42.25	26.95	49.45	0.00
*****TOP WIDTH*******												
R^2	.928	.990	.954	.973	.979	.989	.958	.938	.976	.957	.962	.982
*TW=A(D)^B * A	52.628	22.934	30.502	24.262	15.442	11.580	27.590	24.922	18.152	39.844	20.352	10.470
TW & D, MM B	.506	.660	.587	.640	.722	.787	.599	.621	.693	.535	.666	.799
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	52.404	22.896	30.386	24.208	15.470	11.632	27.460	24.810	18.144	39.652	20.302	10.602
WP & D, MM B	.512	.671	.597	.650	.736	.801	.610	.634	.705	.544	.679	.814
SURF. SHAPE FACT.												
*PROFILE *	.036	.021	.018	.024	.030	.117	.445	.268	.340	.395	.741	.563
*DEPTH *	.227	.133	.114	.149	.190	.200	.239	.179	.249	.292	.574	.560
*ADVANCE *	6.287	6.287	6.287	6.287	6.287	1.714	.536	.669	.730	.740	.775	.699

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
1.91	4.096	0.000	52.3	0.0										
2.13	4.119	0.000	58.4	58.5	0.0									
2.38	4.120	0.000	65.2	65.4	73.4	0.0								
2.54	4.121	0.000	69.5	69.7	78.2	59.5	0.0							
7.12	4.131	0.000	92.6	97.2	110.6	95.3	87.7	0.0						
9.02	4.145	0.000	97.1	101.5	114.8	100.2	93.8	67.8	0.0					
15.42	4.161	0.000	106.5	111.0	124.6	111.2	106.3	95.0	67.8	0.0				
21.52	4.167	0.000	110.4	118.3	129.4	115.9	112.9	105.8	88.6	71.4	0.0			
27.62	4.167	0.000	115.5	119.8	133.4	120.9	117.4	111.2	97.0	82.6	67.3	0.0		
34.02	4.167	0.000	120.0	124.5	138.4	125.5	122.6	117.7	104.9	92.2	82.9	68.7	0.0	
40.42	4.142	0.000	122.4	127.2	141.0	128.5	125.8	121.6	110.0	98.4	91.6	83.6	32.7	0.0
50.00	4.111	0.000	125.7	130.4	144.4	132.4	129.5	126.0	115.4	104.8	100.3	98.9	62.4	88.8
60.00	4.110	0.000	130.0	134.1	146.0	135.3	132.6	130.0	120.7	111.9	111.8	116.6	84.4	115.1
70.00	-2.609	0.000	31.8	50.0	73.7	73.7	82.0	99.8	101.1	102.0	108.9	117.7	87.7	117.3
80.00	-2.028	0.000	20.1	37.9	61.5	60.2	67.3	82.1	82.5	83.0	89.5	97.5	67.8	98.6
90.00	-1.168	0.000	17.0	29.7	52.2	48.7	54.8	67.9	67.5	67.0	73.5	81.7	51.4	82.3
100.00	-.641	0.000	14.6	24.0	45.2	40.5	45.8	58.5	57.3	56.5	62.3	70.7	40.8	70.9
110.00	-.361	0.000	11.2	19.3	38.8	32.5	37.3	50.1	48.6	47.3	53.4	61.4	31.1	61.3
120.00	-.169	0.000	8.9	17.1	34.1	26.2	29.7	42.5	40.9	39.2	45.0	52.7	22.3	53.2
130.00	-.083	0.000	6.5	13.6	29.4	20.0	22.0	36.8	35.0	33.1	38.7	46.5	16.2	46.2
140.00	-.029	0.000	1.8	9.2	24.2	14.5	15.6	31.1	28.6	26.2	30.1	37.2	6.4	37.1
150.00	-.010	0.000	0.0	3.8	17.6	7.6	9.6	24.5	22.0	19.4	21.0	28.4	0.0	27.6
160.00	-.008	0.000	0.0	0.0	10.8	1.0	2.7	18.1	14.6	11.2	12.7	19.2	0.0	16.8
170.00	-.007	0.000	0.0	0.0	2.5	0.0	0.0	10.1	5.7	1.1	1.3	7.2	0.0	4.6
180.00	-.005	0.000	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0
183.00	-.004	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 63.71 MM M2/M/M
DRAINBACK VOLUME = 20.11 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.138 L/S
INFLOW TIME = 62.57 MIN
AVE. SLOPE = -.00002 M/M
AVE. TOP WIDTH A = 23.299
AVE. TOP WIDTH B = .644
AVE. WET PERIM A = 23.159
AVE. WET PERIM B = .657
AVE. SHAPE PROF = .221
AVE. SHAPE DEPTH = .259
AVE. SHAPE ADVAN = 1.049

Table 43. Water surface profile data for Test Number 142, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 142

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	33	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.21	21.10	17.25	3.04	9.58	0.00	6.07	35.96	14.32	19.50	20.42	24.48	23.12	12.23	8.42	20.98
*****TOP WIDTH*******																
R^2	.970	.851	.934	.956	.961	.987	.964	.946	.987	.992	.972	.985	.981	.957	.979	.981
*TW=A(D)^B * A	36.904	98.484	73.492	9.520	16.950	19.278	8.694	22.086	26.366	26.004	26.496	19.846	24.688	53.438	23.356	11.460
TW & D, MM B	.556	.337	.332	.832	.730	.681	.838	.632	.623	.619	.617	.680	.625	.468	.642	.801
*****WETTED PER*******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	36.830	98.232	73.226	9.702	17.006	19.254	8.894	21.982	26.292	25.902	26.426	19.828	24.606	53.144	23.284	11.596
WP & D, MM B	.563	.341	.338	.844	.740	.693	.853	.646	.633	.630	.627	.692	.637	.476	.653	.812
SURF. SHAPE FACT.																
*PROFILE *	.071	.062	.063	.059	.092	.218	.301	.347	.247	.755	.167	.691	.341	.318	.323	0.000
*DEPTH *	.178	.155	.156	.149	.229	.167	.214	.270	.257	.384	.193	.427	.262	.275	.439	.696
*ADVANCE *	2.500	2.500	2.500	2.500	2.500	.766	.713	.779	1.040	.509	1.188	.619	.767	.863	1.357	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
1.28	3.971	0.000	30.1	0.0														
1.69	3.997	0.000	39.7	35.9	0.0													
2.23	3.997	0.000	52.4	47.9	47.2	0.0												
2.63	3.997	0.000	61.6	56.6	56.1	56.8	0.0											
6.17	3.997	0.000	81.0	76.8	79.2	83.4	64.0	0.0										
10.47	3.997	0.000	87.1	85.0	89.7	96.7	82.3	87.9	0.0									
15.67	3.997	0.000	94.1	91.7	97.0	105.3	92.2	106.7	82.7	0.0								
20.87	3.997	0.000	98.8	96.7	102.2	111.1	98.5	115.4	98.6	58.6	0.0							
24.87	3.997	0.000	101.7	99.3	105.3	114.3	102.3	120.5	106.3	69.5	58.9	0.0						
33.66	3.997	0.000	106.0	104.1	110.0	119.4	108.4	128.5	117.3	83.8	83.0	60.5	0.0					
37.67	3.997	0.000	107.9	105.5	111.6	121.3	109.5	130.5	119.7	87.4	88.7	70.9	58.8	0.0				
45.56	3.997	0.000	110.7	108.4	114.7	124.3	112.4	133.5	123.8	93.7	96.4	82.2	76.0	53.8	0.0			
52.27	3.997	0.000	112.4	109.7	115.9	125.5	114.3	136.0	127.3	97.3	101.6	88.4	84.8	69.9	63.9	0.0		
58.37	3.997	0.000	114.1	111.2	117.4	126.9	116.1	138.3	129.7	100.3	104.5	93.3	89.9	77.4	75.9	60.1	0.0	
61.47	3.997	0.000	115.0	111.9	118.3	127.9	116.9	139.2	130.2	100.8	106.3	94.5	92.1	80.4	79.1	67.1	43.4	0.0
70.00	3.991	0.000	116.6	113.7	120.1	130.4	120.1	142.6	134.7	106.3	112.0	101.4	99.9	88.6	89.4	87.7	76.4	61.4
80.00	3.974	0.000	117.6	115.1	121.4	131.6	120.8	143.1	135.4	107.2	114.7	104.2	105.1	97.7	101.8	108.9	105.7	96.2
90.00	3.956	0.000	117.7	114.2	123.9	131.4	122.7	147.1	139.7	112.5	119.7	112.3	115.4	110.2	117.1	126.2	122.6	112.3
100.00	-2.150	0.000	39.5	43.7	66.9	84.3	79.0	114.9	117.3	98.6	112.5	110.1	115.1	112.4	120.1	130.1	126.4	115.3
110.00	-2.383	0.000	28.6	35.1	56.7	73.6	68.0	102.6	105.7	86.7	100.9	99.1	104.9	102.1	110.6	120.7	117.7	106.5
120.00	-1.627	0.000	22.2	30.2	50.2	66.1	60.0	93.7	95.5	76.6	88.4	86.6	90.2	87.8	95.5	105.0	105.0	93.6
130.00	-1.133	0.000	16.1	25.0	45.1	59.7	53.2	85.3	86.4	66.2	79.8	76.7	81.9	79.5	88.1	98.6	95.1	84.3
140.00	-.788	0.000	10.8	21.1	40.1	54.3	47.6	78.7	79.7	60.3	73.2	70.4	75.8	72.6	81.0	92.2	87.3	76.7
150.00	-.545	0.000	7.2	18.4	36.5	50.1	42.4	73.0	73.3	53.0	65.9	63.3	67.7	64.6	72.6	82.6	79.8	68.7
160.00	-.371	0.000	3.9	15.7	32.7	45.6	37.5	66.7	66.5	45.8	59.0	55.4	60.9	58.3	66.7	77.2	73.6	63.2
170.00	-.253	0.000	2.7	14.4	30.3	42.5	33.9	62.7	61.8	39.6	53.9	48.8	54.4	51.8	60.1	70.0	66.4	56.2
180.00	-.162	0.000	1.1	12.5	26.8	38.9	29.8	58.2	56.6	35.1	47.3	43.7	46.4	43.8	51.0	60.8	58.4	47.6
190.00	-.088	0.000	0.0	9.8	23.3	35.2	25.7	53.8	51.8	30.1	42.7	39.0	43.3	38.9	46.6	57.3	52.5	41.6
200.00	-.043	0.000	0.0	7.2	20.0	31.3	22.1	49.2	47.3	25.0	36.9	33.9	36.3	32.5	40.0	49.7	47.1	35.8
210.00	-.016	0.000	0.0	3.7	16.5	27.8	18.7	46.5	43.7	21.9	30.6	27.5	31.7	28.0	36.0	45.5	41.9	31.5
220.00	-.009	0.000	0.0	.9	13.0	24.3	14.8	41.9	39.8	17.9	25.3	21.3	25.2	20.7	28.2	37.7	33.8	23.1
230.00	-.008	0.000	0.0	0.0	8.3	20.4	10.6	38.1	35.0	12.4	17.6	13.0	15.6	11.9	19.9	27.7	23.6	12.9
240.00	-.007	0.000	0.0	0.0	1.5	16.5	7.1	34.3	30.4	8.0	12.3	4.6	8.4	4.0	14.0	20.4	12.0	4.0
250.00	-.006	0.000	0.0	0.0	0.0	13.1	3.3	29.6	25.3	2.5	6.6	0.0	.8	0.0	7.2	8.7	0.0	0.0
260.00	-.006	0.000	0.0	0.0	0.0	9.2	0.0	25.5	20.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270.00	-.005	0.000	0.0	0.0	0.0	4.4	0.0	19.2	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280.00	-.005	0.000	0.0	0.0	0.0	0.0	0.0	9.8	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
288.60	0.000	0.000	0.0	0.0	0.0	0.0	0.0	2.6	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 61.73 MM M2/M/M
DRAINBACK VOLUME = 17.88 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.988 L/S
INFLOW TIME = 92.60 MIN
AVE. SLOPE = .00001 M/M
AVE. TOP WIDTH A = 25.791
AVE. TOP WIDTH B = .621
AVE. WET PERIM A = 25.573
AVE. WET PERIM B = .634
AVE. SHAPE PROF = .270
AVE. SHAPE DEPTH = .279
AVE. SHAPE ADVAN = .960

Table 44. Water surface profile data for Test Number 143, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 143

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	18	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		0.00	18.18	15.61	6.24	5.39	31.54	21.13	28.33
*****TOP WIDTH*******									
	R^2	.987	.943	.972	.977	.969	.959	.951	.836
*TW=A(D)^B *	A	13.080	64.516	28.106	31.236	19.702	2.508	12.774	32.812
TW & D, MM	B	.771	.441	.615	.580	.683	1.043	.775	.574
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	13.180	64.250	28.048	31.096	19.696	3.204	12.870	32.640
WP & D, MM	B	.783	.447	.624	.590	.694	1.028	.788	.585
SURF. SHAPE FACT.									
*PROFILE *		.212	.297	.344	.368	.363	.731	.367	.347
*DEPTH *		.145	.203	.235	.251	.248	.409	.354	.571
*ADVANCE *		.683	.683	.683	.683	.683	.559	.964	.779

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.08	3.751	0.000	3.3	0.0						
.23	4.167	0.000	9.2	6.5	0.0					
.64	4.167	0.000	25.5	18.0	16.5	0.0				
1.15	4.167	0.000	46.1	32.5	29.9	29.3	0.0			
4.32	4.167	0.000	100.0	75.5	74.0	77.0	77.0	0.0		
8.92	4.167	0.000	112.5	90.1	89.0	94.5	96.6	54.7	0.0	
12.02	4.167	0.000	117.5	95.9	95.0	100.2	102.5	65.4	59.8	0.0
20.00	4.167	0.000	127.3	107.1	107.1	112.1	114.8	85.9	98.7	89.2
30.00	-.802	0.000	61.8	47.7	54.6	71.8	81.4	71.5	94.9	86.8
40.00	-1.576	0.000	41.5	27.5	34.3	47.4	55.2	41.5	61.2	54.0
50.00	-.455	0.000	30.7	17.3	23.6	34.8	41.4	26.2	45.3	37.0
60.00	-.143	0.000	22.2	11.4	17.2	26.6	32.7	14.8	34.8	25.9
70.00	-.046	0.000	15.7	5.3	11.6	21.5	26.5	7.9	26.4	18.6
80.00	-.008	0.000	11.1	0.0	6.5	16.2	22.0	1.8	20.3	12.8
90.00	-.005	0.000	0.0	0.0	.1	6.8	12.8	0.0	10.5	3.5
100.00	-.004	0.000	0.0	0.0	0.0	0.0	7.2	0.0	.2	0.0
108.00	-.002	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 50.19 MM M2/M/M
DRAINBACK VOLUME = 24.15 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.166 L/S
INFLOW TIME = 24.40 MIN
AVE. SLOPE = .00018 M/M
AVE. TOP WIDTH A = 21.375
AVE. TOP WIDTH B = .659
AVE. WET PERIM A = 21.296
AVE. WET PERIM B = .672
AVE. SHAPE PROF = .383
AVE. SHAPE DEPTH = .302
AVE. SHAPE ADVAN = .622

Table 45. Water surface profile data for Test Number 144, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 144

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	24	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM		30.35	31.51	19.42	32.99	34.33	34.45	48.75	48.36	42.25	26.95	49.45	0.00
*****TOP WIDTH*******													
	R^2	.928	.990	.954	.973	.979	.989	.958	.938	.976	.957	.962	.982
*TW=A(D)^B *	A	52.628	22.934	30.502	24.262	15.442	11.580	27.590	24.922	18.152	39.844	20.352	10.470
TW & D, MM	B	.506	.660	.587	.640	.722	.787	.599	.621	.693	.535	.666	.799
*****WETTED PER******													
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	52.404	22.896	30.386	24.208	15.470	11.692	27.460	24.810	18.144	39.652	20.302	10.602
WP & D, MM	B	.512	.671	.597	.650	.736	.801	.610	.634	.705	.544	.679	.814
SURF. SHAPE FACT.													
*PROFILE	*	.073	.045	.038	.049	.059	.075	.598	.214	.840	1.000	.767	.691
*DEPTH	*	.250	.156	.131	.169	.204	.174	.287	.215	.589	.549	.535	.571
*ADVANCE	*	3.443	3.443	3.443	3.443	3.443	2.334	.479	1.003	.702	.480	.697	.619

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
1.34	4.145	0.000	41.0	0.0										
1.64	4.176	0.000	50.2	52.9	0.0									
2.01	4.178	0.000	61.4	64.7	70.3	0.0								
2.26	4.180	0.000	66.4	72.6	79.1	56.4	0.0							
6.85	4.195	0.000	88.9	95.5	106.4	91.1	85.3	0.0						
8.15	4.213	0.000	92.0	99.5	109.8	95.6	90.4	59.7	0.0					
14.85	4.223	0.000	102.5	109.5	120.9	107.4	104.3	93.1	64.6	0.0				
18.55	4.224	0.000	106.7	113.7	124.8	111.3	108.5	99.5	80.6	61.7	0.0			
24.05	4.224	0.000	110.6	118.5	129.4	116.6	114.1	107.8	91.5	75.5	47.3	0.0		
33.15	4.224	0.000	116.7	124.0	135.4	121.2	119.8	114.8	101.5	88.1	78.9	61.2	0.0	
40.15	4.224	0.000	118.9	126.9	138.2	124.8	123.2	119.2	107.1	95.0	88.3	80.6	33.4	0.0
50.00	4.224	0.000	122.2	130.1	141.2	128.4	126.4	123.7	113.4	102.8	99.3	98.7	63.2	91.8
60.00	4.224	0.000	99.0	111.4	129.7	125.5	121.5	125.9	119.0	111.2	110.4	114.1	85.2	116.1
70.00	-3.678	0.000	27.4	48.9	67.4	64.2	73.5	89.6	90.8	92.0	99.3	107.6	79.5	109.4
80.00	-1.655	0.000	19.6	39.3	56.1	50.1	58.1	72.8	72.7	73.5	81.6	90.6	62.2	90.7
90.00	-.892	0.000	15.1	32.4	48.4	41.9	48.0	61.1	60.9	61.2	67.6	76.2	48.5	76.3
100.00	-.466	0.000	10.5	27.1	41.8	33.1	38.2	50.2	49.1	48.2	53.7	62.0	33.3	62.5
110.00	-.209	0.000	6.6	22.8	35.6	25.8	28.7	41.5	39.9	38.1	44.5	52.2	23.2	52.9
120.00	-.073	0.000	1.2	16.9	29.7	19.0	21.2	34.4	32.1	29.6	35.2	42.8	13.5	42.6
130.00	-.012	0.000	0.0	11.2	22.6	11.2	12.9	26.2	23.6	20.8	25.6	33.2	4.6	33.3
140.00	-.007	0.000	0.0	3.2	12.2	2.6	4.8	17.5	14.5	11.0	15.2	21.7	0.0	22.1
150.00	-.006	0.000	0.0	0.0	2.8	0.0	0.0	6.7	3.4	0.0	.2	7.5	0.0	5.7
159.00	-.005	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 63.12 MM M2/M/M
DRAINBACK VOLUME = 18.07 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.219 L/S
INFLOW TIME = 60.80 MIN
AVE. SLOPE = -.00001 M/M
AVE. TOP WIDTH A = 23.299
AVE. TOP WIDTH B = .644
AVE. WET PERIM A = 23.159
AVE. WET PERIM B = .657
AVE. SHAPE PROF = .342
AVE. SHAPE DEPTH = .319
AVE. SHAPE ADVAN = .997

Table 46. Water surface profile data for Test Number 145, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 145

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	35	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.21	21.10	17.25	3.04	9.58	0.00	6.07	35.95	14.32	19.50	20.42	24.48	23.12	12.23	8.42	20.98
*****TOP WIDTH*******																
R^2	.970	.851	.934	.956	.961	.987	.964	.946	.987	.992	.972	.985	.981	.957	.979	.981
*TW=A(D)^B * A	36.904	98.484	73.492	9.520	16.950	19.278	8.634	22.086	26.365	26.004	26.496	19.846	24.688	53.438	23.356	11.460
TW & D, MM B	.556	.337	.392	.832	.730	.681	.838	.632	.623	.619	.617	.680	.625	.468	.642	.801
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	36.830	98.232	73.226	9.702	17.006	19.254	8.684	21.982	26.292	25.902	26.426	19.828	24.606	53.144	23.284	11.596
WP & D, MM B	.563	.341	.398	.844	.740	.693	.853	.646	.633	.630	.627	.692	.637	.476	.653	.812
SURF. SHAPE FACT.																
*PROFILE *	.226	.191	.185	.170	.246	.226	.254	.521	.417	.469	.784	.519	.335	.555	.771	0.000
*DEPTH *	.235	.193	.192	.176	.255	.172	.243	.292	.292	.367	.458	.367	.295	.470	.676	.537
*ADVANCE *	1.036	1.036	1.035	1.035	1.036	.763	.957	.561	.700	.784	.585	.709	.882	.718	.877	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.37	3.963	0.000	36.9	0.0														
.73	4.054	0.000	42.6	36.9	0.0													
1.42	4.056	0.000	48.9	43.3	19.0	0.0												
2.10	4.057	0.000	55.1	49.7	34.8	34.9	0.0											
5.70	4.062	0.000	76.1	73.3	76.3	81.7	63.0	0.0										
9.70	4.071	0.000	83.0	80.6	86.0	93.3	78.7	86.3	0.0									
13.10	4.080	0.000	88.9	86.3	91.7	93.7	85.8	99.3	68.1	0.0								
19.50	4.092	0.000	94.4	92.4	98.7	107.5	95.3	111.1	94.1	54.2	0.0							
25.30	4.106	0.000	98.3	97.0	102.9	111.9	99.6	118.3	104.8	68.0	60.3	0.0						
30.80	4.102	0.000	101.1	99.3	105.8	115.0	102.7	122.5	110.3	76.3	74.8	49.2	0.0					
38.70	4.090	0.000	103.9	102.6	109.0	118.2	106.7	127.5	117.2	84.9	86.6	69.8	60.2	0.0				
45.69	4.075	0.000	105.7	104.6	111.3	120.6	109.4	130.9	120.9	90.2	93.5	78.8	73.3	51.3	0.0			
51.49	4.063	0.000	107.7	106.3	112.7	122.9	111.4	133.1	123.7	94.0	98.2	86.5	80.3	64.4	56.3	0.0		
58.80	4.054	0.000	109.5	108.8	115.3	124.2	113.0	135.5	126.5	97.4	102.1	91.2	87.1	72.9	70.8	53.5	0.0	
63.70	4.053	0.000	109.9	108.9	115.5	124.8	114.0	136.8	128.5	99.7	104.3	93.4	90.4	77.6	76.3	67.6	37.9	0.0
70.00	4.053	0.000	111.1	110.0	116.3	126.6	115.7	138.2	129.9	101.1	106.6	96.8	94.4	82.9	82.9	80.0	67.5	54.7
80.00	4.053	0.000	113.0	111.5	117.7	128.5	117.2	139.9	132.5	104.2	110.2	100.1	99.5	90.1	94.1	93.5	95.7	83.1
90.00	4.053	0.000	117.0	112.7	121.8	128.7	119.2	142.5	135.6	108.1	115.8	106.0	108.7	102.4	108.4	116.8	113.5	101.6
100.00	-1.419	0.000	36.2	46.7	66.3	82.4	77.5	114.4	115.3	95.6	109.7	105.4	109.7	106.5	114.4	124.6	120.6	110.4
110.00	-2.250	0.000	25.8	37.1	54.1	69.9	63.5	98.0	100.4	79.8	93.7	89.5	95.2	92.6	100.4	110.8	109.3	98.4
120.00	-1.424	0.000	18.7	31.0	46.9	62.1	55.3	88.5	89.0	69.6	83.1	81.2	85.1	81.7	89.1	99.0	96.7	85.8
130.00	-.917	0.000	13.8	26.1	42.2	56.1	48.3	80.2	81.1	61.4	74.3	72.0	76.7	73.8	81.8	92.1	89.6	77.5
140.00	-.574	0.000	10.9	20.9	36.4	49.7	41.1	71.9	72.0	51.4	64.7	62.1	66.7	64.0	72.0	82.2	79.1	68.4
150.00	-.336	0.000	8.1	17.4	32.0	44.6	36.0	65.3	65.1	44.7	57.7	53.5	58.7	55.4	63.0	72.6	69.5	58.2
160.00	-.192	0.000	5.0	15.4	29.0	40.6	31.2	60.1	58.6	37.2	50.1	46.6	50.6	46.9	54.5	64.6	62.2	50.2
170.00	-.105	0.000	1.8	12.5	24.4	36.5	26.8	55.5	54.1	31.4	43.5	40.8	44.8	41.7	49.5	59.5	56.4	46.2
180.00	-.032	0.000	0.0	9.3	20.2	31.9	21.3	49.0	46.9	24.7	36.3	32.5	37.5	34.5	42.1	52.0	49.1	38.3
190.00	-.009	0.000	0.0	2.4	14.1	25.8	16.2	44.6	41.7	20.4	28.7	26.8	30.3	27.4	36.1	46.0	42.3	32.0
200.00	-.005	0.000	0.0	0.0	7.7	20.9	11.7	40.4	37.4	16.2	20.4	16.8	21.9	17.9	26.7	36.4	33.1	22.3
210.00	-.004	0.000	0.0	0.0	2.0	15.3	5.8	35.3	31.4	10.6	12.8	10.2	13.2	7.7	17.5	26.1	22.3	11.5
220.00	-.003	0.000	0.0	0.0	0.0	10.6	1.1	30.6	26.0	4.0	6.9	.6	.2	0.0	9.5	16.5	9.9	0.0
230.00	-.004	0.000	0.0	0.0	0.0	4.6	0.0	23.8	19.0	0.0	.4	0.0	0.0	0.0	2.5	4.3	0.0	0.0
240.00	-.003	0.000	0.0	0.0	0.0	0.0	0.0	15.9	13.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	1.6	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250.20	0.000	0.000	0.0	0.0	0.0	0.0	0.0	1.5	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 63.64 MM M2/M/M
DRAINBACK VOLUME = 14.68 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.069 L/S
INFLOW TIME = 93.75 MIN
AVE. SLOPE = .00001 M/M
AVE. TOP WIDTH A = 25.791
AVE. TOP WIDTH B = .621
AVE. WET PERIM A = 25.573
AVE. WET PERIM B = .634
AVE. SHAPE PROF = .338
AVE. SHAPE DEPTH = .327
AVE. SHAPE ADVAN = .795

Table 47. Water surface profile data for Test Number 146, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 146

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	15	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	24.83	35.26	9.45	2.09	0.00	16.70	4.88	1.90
*****TOP WIDTH*******								
R^2	.981	.934	.988	.994	.923	.919	.967	.873
*TW=A(D)^B * A	49.362	51.506	17.874	27.540	34.364	47.248	34.314	29.930
TW & D, MM B	.511	.516	.683	.604	.556	.511	.550	.591
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	49.306	51.414	17.862	27.406	34.192	47.074	34.146	29.834
WP & D, MM B	.516	.521	.697	.616	.566	.518	.560	.600
SURF. SHAPE FACT.								
*PROFILE *	.127	.363	.282	.292	.426	.441	.435	.521
*DEPTH *	.076	.217	.169	.175	.255	.271	.250	.198
*ADVANCE *	.599	.599	.599	.599	.599	.614	.575	.561

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.06	3.516	0.000	2.0	0.0						
.20	4.053	0.000	6.5	4.2	0.0					
.64	4.053	0.000	20.6	13.2	18.4	0.0				
1.25	4.053	0.000	40.6	26.0	36.2	34.1	0.0			
7.48	4.053	0.000	95.9	73.7	101.0	104.3	94.0	0.0		
14.48	4.053	0.000	106.1	86.2	114.1	118.9	110.9	87.7	0.0	
23.88	4.053	0.000	102.1	85.6	114.2	121.1	116.7	100.7	90.7	0.0
30.00	0.000	0.000	73.7	57.1	85.6	92.2	87.7	77.6	90.2	90.0
40.00	0.000	0.000	54.2	37.3	66.0	72.7	68.7	59.6	75.3	76.9
50.00	0.000	0.000	48.2	21.7	50.2	56.8	52.6	44.1	59.4	60.9
60.00	0.000	0.000	46.0	7.2	35.8	42.5	38.4	29.7	43.8	45.6
70.00	0.000	0.000	43.5	0.0	20.1	26.8	21.5	9.8	24.7	28.6
80.00	0.000	0.000	39.2	0.0	.4	7.6	1.1	0.0	0.0	10.5
90.00	0.000	0.000	14.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 48.12 MM M2/M/M
DRAINBACK VOLUME = .02 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.052 L/S
INFLOW TIME = 24.13 MIN
AVE. SLOPE = -.00015 M/M
AVE. TOP WIDTH A = 35.648
AVE. TOP WIDTH B = .560
AVE. WET PERIM A = 35.440
AVE. WET PERIM B = .570
AVE. SHAPE PROF = .338
AVE. SHAPE DEPTH = .201
AVE. SHAPE ADVAN = .519

Table 48. Water surface profile data for Test Number 147, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 147

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	18	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	39.69	30.85	23.27	18.85	18.20	22.61	35.50	24.73	26.50	22.86	20.61	0.00
*****TOP WIDTH*******												
R^2	.987	.987	.983	.986	.989	.995	.906	.952	.993	.962	.991	.988
*TW=A(D)^B * A	34.978	44.156	29.864	33.426	16.390	24.424	43.908	4.778	12.690	14.906	18.732	31.904
TW & D, MM B	.572	.520	.585	.567	.729	.629	.504	.955	.767	.731	.679	.586
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	34.918	44.038	29.770	33.316	16.438	24.378	43.748	5.178	12.788	14.958	18.722	31.816
WP & D, MM B	.579	.526	.595	.576	.740	.639	.512	.963	.780	.744	.692	.594
SURF. SHAPE FACT.												
*PROFILE *	.070	.039	.036	.036	.045	.173	.620	.303	.186	.417	.746	.519
*DEPTH *	.251	.139	.130	.128	.159	.238	.193	.153	.183	.311	.389	.300
*ADVANCE *	3.575	3.575	3.575	3.575	3.575	1.372	.311	.503	.984	.746	.522	.709

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
1.69	4.033	0.000	37.2	0.0										
2.05	4.053	0.000	45.2	53.9	0.0									
2.49	4.053	0.000	54.8	65.5	65.0	0.0								
2.79	4.053	0.000	60.4	73.3	72.8	66.7	0.0							
6.23	4.053	0.000	75.1	90.2	93.5	92.1	89.4	0.0						
8.38	4.053	0.000	80.1	95.3	99.1	98.5	97.8	49.1	0.0					
21.13	4.053	0.000	93.3	109.1	113.3	114.4	115.4	97.3	97.3	0.0				
32.93	4.041	0.000	99.2	114.8	119.5	120.4	121.2	108.9	108.9	86.5	0.0			
39.63	4.021	0.000	101.9	118.1	123.8	124.4	124.8	113.6	113.6	93.6	64.0	0.0		
48.73	4.005	0.000	106.9	124.0	128.7	130.3	126.5	116.4	116.4	101.8	80.7	61.9	0.0	
62.93	3.842	0.000	99.7	116.1	122.2	124.9	122.9	119.0	119.0	109.3	91.1	72.8	56.9	0.0
70.00	0.000	0.000	72.1	88.6	94.7	98.1	96.6	94.6	94.6	96.7	87.7	80.7	66.8	70.1
80.00	0.000	0.000	48.8	59.6	65.6	69.2	72.9	70.6	70.6	73.1	65.2	60.5	59.1	64.5
90.00	0.000	0.000	33.0	44.1	50.2	54.1	57.2	55.7	55.7	59.7	50.4	48.6	41.3	48.5
100.00	0.000	0.000	24.1	35.2	41.2	45.2	45.8	43.6	43.6	46.6	34.1	32.1	29.7	34.7
110.00	0.000	0.000	8.9	20.5	26.8	31.0	35.0	33.9	33.9	38.2	21.5	20.2	11.7	18.3
114.60	0.000	0.000	1.4	11.0	16.0	19.5	22.3	19.3	19.3	20.6	6.2	3.7	0.0	.7

INFLOW VOLUME = 61.82 MM M2/M/M
DRAINBACK VOLUME = .02 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.027 L/S
INFLOW TIME = 62.38 MIN
AVE. SLOPE = -.00006 M/M
AVE. TOP WIDTH A = 23.351
AVE. TOP WIDTH B = .642
AVE. WET PERIM A = 23.216
AVE. WET PERIM B = .654
AVE. SHAPE PROF = .243
AVE. SHAPE DEPTH = .215
AVE. SHAPE ADVAN = .896

Table 49. Water surface profile data for Test Number 148, Table 1.

NAC FURROW DRAINBACK STUDY NUMBER 148

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	25	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.42	12.07	16.71	9.51	1.56	0.00	.64	22.98	11.89	7.75	23.44	17.08	10.17	19.59	8.94	18.73
*****TOP WIDTH*******																
R^2	.934	.933	.957	.894	.964	.994	.988	.946	.984	.978	.942	.976	.991	.988	.985	.967
*TW=A(D)^B * A	71.390	50.234	62.939	26.100	31.044	19.704	25.088	45.340	23.616	57.152	66.616	49.688	39.844	27.830	18.278	19.430
TW & D, MM B	.432	.478	.432	.627	.586	.673	.629	.512	.596	.456	.423	.491	.528	.612	.705	.682
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	71.270	50.070	62.728	26.072	30.954	19.688	25.032	45.196	29.538	56.894	66.310	49.522	39.634	27.758	18.296	19.444
WP & D, MM B	.435	.485	.438	.635	.595	.685	.639	.519	.605	.463	.430	.498	.537	.622	.716	.692
SURF. SHAPE FACT.																
*PROFILE *	.101	.074	.078	.100	.109	1.000	.521	.513	.614	.871	.483	.752	.482	.541	.192	0.000
*DEPTH *	.128	.094	.099	.127	.138	.572	.315	.284	.460	.390	.339	.395	.208	.224	.136	.804
*ADVANCE *	1.269	1.269	1.269	1.269	1.269	.400	.604	.553	.749	.447	.701	.525	.433	.415	.707	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.82	4.012	0.000	31.2	0.0														
1.42	4.053	0.000	53.9	59.9	0.0													
1.83	4.053	0.000	69.3	77.0	65.1	0.0												
3.38	4.053	0.000	79.8	92.0	82.5	73.1	0.0											
3.98	4.053	0.000	81.9	94.0	84.8	76.5	59.8	0.0										
10.98	4.053	0.000	93.6	106.7	99.7	97.8	97.3	63.3	0.0									
17.68	4.053	0.000	99.1	112.2	105.7	105.4	105.9	98.5	87.9	0.0								
26.48	4.053	0.000	103.8	117.3	111.2	111.6	113.3	109.2	106.1	62.0	0.0							
33.78	4.047	0.000	106.9	120.6	114.6	115.7	118.0	116.3	113.0	76.4	69.7	0.0						
47.68	4.034	0.000	110.6	124.1	118.1	119.9	122.3	121.7	120.8	83.5	85.2	69.2	0.0					
57.68	4.029	0.000	112.4	126.0	120.1	121.7	124.5	124.0	123.4	93.9	90.8	77.0	45.8	0.0				
72.18	4.040	0.000	114.6	128.3	122.9	125.1	128.0	128.4	128.6	99.8	97.8	85.6	59.7	48.4	0.0			
92.08	4.060	0.000	116.7	130.2	125.0	127.7	131.1	131.8	132.5	105.0	104.7	92.9	68.5	57.4	57.8	0.0		
115.88	4.101	0.000	119.0	132.6	127.6	130.8	131.9	133.4	134.3	109.0	108.9	98.1	74.0	65.8	68.4	46.6	0.0	
127.98	3.750	0.000	106.6	120.1	115.7	121.0	123.0	127.7	132.0	106.2	108.8	98.4	75.6	68.5	71.5	50.7	41.7	0.0
130.00	0.000	0.000	97.5	111.4	107.4	113.2	116.1	122.8	123.1	104.1	108.1	98.2	75.6	68.7	72.2	51.6	43.6	18.3
140.00	0.000	0.000	69.6	83.7	79.4	84.6	87.9	97.8	108.4	86.9	92.6	87.7	69.3	65.6	73.3	56.7	56.4	47.2
150.00	0.000	0.000	49.8	63.9	59.9	65.2	68.8	78.4	88.2	66.6	74.0	69.3	53.5	52.7	62.9	51.1	56.9	48.6
160.00	0.000	0.000	32.7	46.9	42.7	47.8	51.9	62.0	71.3	47.8	56.7	52.1	36.5	35.3	47.8	39.2	46.5	38.8
170.00	0.000	0.000	18.0	31.9	27.3	31.4	35.9	45.2	54.5	27.7	33.6	30.3	10.4	9.3	18.9	7.4	16.3	8.8
180.00	0.000	0.000	1.6	18.4	10.3	17.5	22.1	31.8	40.5	9.0	13.3	5.2	0.0	0.0	0.0	0.0	0.0	0.0
190.00	0.000	0.000	0.0	.8	0.0	2.4	6.5	13.9	20.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200.40	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 86.00 MM M2/M/M
DRAINBACK VOLUME = -.01 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.062 L/S
INFLOW TIME = 126.92 MIN
AVE. SLOPE = .00002 M/M
AVE. TOP WIDTH A = 37.105
AVE. TOP WIDTH B = .549
AVE. WET PERIM A = 36.882
AVE. WET PERIM B = .558
AVE. SHAPE PROF = .429
AVE. SHAPE DEPTH = .295
AVE. SHAPE ADVAN = .769

Table 50. Water surface profile data for Test Number 149, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 149

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	28	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM	24.83	36.26	9.45	2.09	0.00	16.70	4.88	1.90
*****TOP WIDTH*******								
R^2	.981	.934	.988	.994	.923	.919	.967	.873
*TW=A(D)^B * A	49.352	51.506	17.874	27.540	34.364	47.248	34.314	29.930
TW & D, MM B	.511	.516	.683	.604	.556	.511	.550	.591
*****WETTED PER******								
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	49.306	51.414	17.862	27.406	34.192	47.074	34.146	29.834
WP & D, MM B	.516	.521	.697	.616	.566	.518	.560	.600
SURF. SHAPE FACT.								
*PROFILE *	.077	.458	.336	.324	.538	.158	.240	.513
*DEPTH *	.046	.275	.202	.194	.323	.132	.136	.009
*ADVANCE *	.600	.600	.600	.600	.600	.837	.568	.553

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.07	3.605	0.000	4.4	0.0						
.22	4.110	0.000	13.9	6.4	0.0					
.69	4.110	0.000	44.2	20.3	29.7	0.0				
1.35	4.110	0.000	86.9	39.9	58.3	56.1	0.0			
7.38	4.110	0.000	99.0	72.5	99.5	103.0	93.8	0.0		
11.98	4.110	0.000	105.0	82.7	110.6	116.5	106.9	82.5	0.0	
19.88	3.426	0.000	92.9	74.3	103.0	110.3	104.5	90.3	90.2	0.0
20.00	0.000	0.000	92.4	73.8	102.4	109.9	103.9	90.1	90.4	87.1
30.00	0.000	0.000	71.0	54.0	82.9	89.5	85.4	77.3	94.7	95.3
40.00	0.000	0.000	64.5	49.9	80.1	81.8	80.1	71.6	88.0	88.8
50.00	0.000	0.000	62.2	44.0	73.3	80.5	75.0	66.7	82.6	84.2
60.00	0.000	0.000	57.6	40.3	68.9	76.1	70.9	62.3	78.5	80.1
70.00	0.000	0.000	52.9	35.6	64.4	71.5	65.6	57.5	73.6	74.8
80.00	0.000	0.000	49.5	31.0	59.8	66.5	61.3	53.1	69.3	70.0
90.00	0.000	0.000	46.5	25.7	54.7	61.8	57.0	49.0	65.9	67.5
100.00	0.000	0.000	43.5	22.2	51.3	58.0	52.8	44.9	61.0	61.5
110.00	0.000	0.000	40.7	17.3	46.5	53.6	48.8	41.1	56.6	58.7
120.00	0.000	0.000	37.5	14.1	43.1	49.7	44.4	35.9	50.4	51.7
130.00	0.000	0.000	31.9	7.8	37.5	44.0	40.0	32.9	45.8	47.6
140.00	0.000	0.000	27.5	2.8	32.4	38.9	34.8	28.4	40.0	40.9
150.00	0.000	0.000	23.6	0.0	27.1	33.6	30.0	22.8	34.0	35.4
160.00	0.000	0.000	20.2	0.0	22.7	28.9	25.0	17.6	26.9	28.7
170.00	0.000	0.000	15.2	0.0	16.8	22.7	19.5	11.5	19.6	21.5
180.00	0.000	0.000	12.1	0.0	11.7	15.1	14.1	3.4	12.2	15.5
190.00	0.000	0.000	6.2	0.0	4.3	8.9	8.7	0.0	3.0	11.7
200.00	0.000	0.000	0.0	0.0	0.0	1.5	1.7	0.0	0.0	4.0
200.40	0.000	0.000	0.0	0.0	0.0	1.3	1.5	0.0	0.0	3.8

INFLOW VOLUME = 37.54 MM M2/M/M
DRAINBACK VOLUME = .09 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.105 L/S
INFLOW TIME = 18.58 MIN
AVE. SLOPE = -.00015 M/M
AVE. TOP WIDTH A = 35.648
AVE. TOP WIDTH B = .560
AVE. WET PERIM A = 35.440
AVE. WET PERIM B = .570
AVE. SHAPE PROF = .304
AVE. SHAPE DEPTH = .165
AVE. SHAPE ADVAN = .545

Table 51. Water surface profile data for Test Number 150, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 150

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	31	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM		39.69	30.85	23.27	18.85	18.20	22.61	35.50	24.73	26.50	22.86	20.61	0.00
*****TOP WIDTH*******													
	R^2	.987	.997	.983	.986	.989	.995	.906	.952	.993	.962	.991	.988
*TW=A(D)^B *	A	34.978	44.155	29.864	33.426	16.390	24.424	43.908	4.778	12.690	14.906	18.732	31.904
TW & D, MM	B	.572	.520	.585	.567	.729	.629	.504	.955	.767	.731	.679	.586
*****WETTED PER******													
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	34.918	44.038	29.770	33.316	16.438	24.378	43.748	5.178	12.788	14.958	18.722	31.816
WP & D, MM	B	.579	.526	.595	.576	.740	.639	.512	.963	.780	.744	.692	.594
SURF. SHAPE FACT.													
*PROFILE	*	.424	.371	.358	.367	.297	.204	1.000	.168	.066	.464	.512	.752
*DEPTH	*	.207	.181	.173	.179	.145	.325	.524	.123	.092	.211	.299	.217
*ADVANCE	*	.487	.487	.487	.487	.487	1.591	.344	.731	1.393	.454	.584	.525

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.07	3.595	0.000	1.7	0.0										
.31	4.053	0.000	6.9	8.3	0.0									
1.27	4.053	0.000	28.7	34.4	34.1	0.0								
2.93	4.053	0.000	63.9	78.8	79.1	72.7	0.0							
6.02	4.053	0.000	74.3	89.2	91.9	90.5	83.7	0.0						
7.76	4.053	0.000	78.3	94.0	97.4	97.7	95.2	48.6	0.0					
17.92	4.053	0.000	93.3	109.4	113.6	114.5	114.5	101.2	73.6	0.0				
24.32	4.053	0.000	98.5	113.3	119.6	121.8	121.9	109.3	96.8	84.2	0.0			
27.72	4.053	0.000	89.4	109.1	110.5	113.4	115.1	110.8	100.7	89.9	62.9	0.0		
38.92	4.053	0.000	90.2	106.8	110.9	111.2	111.2	99.7	92.1	81.7	68.7	61.6	0.0	
48.92	-5.696	0.000	103.0	120.1	119.9	123.5	120.6	114.3	107.6	99.8	85.1	74.9	55.0	0.0
50.00	0.000	0.000	97.6	115.0	117.0	119.9	117.5	114.7	103.1	101.4	87.1	76.1	57.3	21.9
60.00	0.000	0.000	70.5	87.2	93.3	96.6	95.0	92.7	92.9	92.8	86.7	83.5	76.7	80.4
70.00	0.000	0.000	62.2	78.6	84.0	87.3	85.7	83.9	85.0	86.0	81.6	82.7	77.0	83.2
80.00	0.000	0.000	55.0	71.6	77.9	81.2	79.5	77.6	80.0	82.1	77.4	77.9	71.3	76.5
90.00	0.000	0.000	50.9	67.7	73.1	76.6	75.7	74.1	75.7	77.0	72.8	72.7	67.0	72.6
100.00	0.000	0.000	47.8	64.7	70.7	74.1	72.4	70.9	72.5	74.0	68.5	67.2	62.0	66.9
110.00	0.000	0.000	43.4	59.9	65.5	69.1	67.6	65.4	66.4	67.3	62.4	61.7	55.0	60.0
120.00	0.000	0.000	37.3	54.1	60.0	63.6	61.9	60.2	62.0	63.5	56.9	57.3	50.8	56.6
130.00	0.000	0.000	31.8	48.6	54.2	58.4	57.0	55.9	57.6	59.7	53.9	53.5	48.2	53.8
140.00	0.000	0.000	25.1	41.9	47.9	51.7	50.8	49.9	52.4	54.7	49.1	48.5	42.8	48.1
150.00	0.000	0.000	22.4	39.0	45.1	48.4	47.1	45.5	47.0	48.4	41.9	42.4	34.4	39.9
160.00	0.000	0.000	16.1	32.7	39.2	42.9	41.5	40.5	43.3	45.5	38.7	37.5	30.5	35.4
170.00	0.000	0.000	11.2	28.0	34.9	38.2	37.3	36.5	39.3	42.2	34.7	32.2	26.3	30.9
180.00	0.000	0.000	3.3	16.5	21.9	26.0	29.8	28.6	31.6	34.9	25.9	23.4	15.8	20.0
190.00	0.000	0.000	0.0	9.8	16.2	21.4	26.3	25.6	27.4	29.5	16.9	13.0	3.9	6.1
200.00	0.000	0.000	0.0	5.3	11.5	16.5	21.1	20.2	22.1	24.0	9.8	3.7	0.0	0.0
210.00	0.000	0.000	0.0	0.0	4.3	10.5	16.3	14.9	17.7	19.2	5.2	0.0	0.0	0.0
220.00	0.000	0.000	0.0	0.0	0.0	2.7	8.7	5.0	7.3	9.4	0.0	0.0	0.0	0.0
222.60	0.000	0.000	0.0	0.0	0.0	1.0	7.1	3.3	5.5	7.7	0.0	0.0	0.0	0.0

INFLOW VOLUME = 41.07 MM M2/M/M
DRAINBACK VOLUME = .01 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.395 L/S
INFLOW TIME = 49.17 MIN
AVE. SLOPE = -.00006 M/M
AVE. TOP WIDTH A = 23.351
AVE. TOP WIDTH B = .642
AVE. WET PERIM A = 23.216
AVE. WET PERIM B = .654
AVE. SHAPE PROF = .386
AVE. SHAPE DEPTH = .223
AVE. SHAPE ADVAN = .620

Table 52. Water surface profile data for Test Number 151, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 151

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	31	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.42	12.07	16.71	9.51	1.56	0.00	.64	22.98	11.83	7.75	23.44	17.08	10.17	19.58	8.94	18.73
*****TOP WIDTH******																
R^2	.934	.933	.957	.834	.954	.934	.988	.946	.984	.978	.942	.976	.991	.988	.985	.967
*TW=A(D)^B * A	71.330	50.234	62.938	26.100	31.044	19.704	25.088	45.340	23.616	57.152	66.616	49.688	39.844	27.830	18.278	19.430
TW & D, MM B	.432	.478	.432	.627	.586	.673	.623	.512	.596	.456	.423	.491	.528	.612	.705	.682
*****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	71.270	50.070	62.728	26.072	30.954	19.688	25.032	45.196	29.538	56.894	66.310	49.522	33.694	27.758	18.296	19.444
WP & D, MM B	.436	.485	.438	.636	.595	.685	.639	.519	.605	.463	.430	.498	.537	.622	.716	.692
SURF. SHAPE FACT.																
*PROFILE *	.233	.167	.743	.187	.175	.269	.331	.459	.158	.360	.439	.244	.584	.599	1.000	0.000
*DEPTH *	.184	.132	.586	.148	.138	.206	.219	.291	.143	.255	.278	.222	.364	.446	.692	.211
*ADVANCE *	.789	.789	.789	.789	.789	.767	.662	.634	.904	.710	.632	.908	.623	.745	.591	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.33	4.061	0.000	40.7	0.0														
.54	4.167	0.000	50.9	61.2	0.0													
1.90	4.167	0.000	62.8	73.0	34.2	0.0												
3.17	4.167	0.000	74.0	84.1	62.6	62.2	0.0											
6.60	4.167	0.000	83.6	97.8	90.3	86.1	82.5	0.0										
11.20	4.167	0.000	90.8	104.5	97.6	96.4	96.0	96.9	0.0									
17.30	4.167	0.000	95.8	109.8	103.5	103.7	105.0	111.7	95.3	0.0								
24.60	4.167	0.000	101.5	115.6	109.6	110.7	112.8	124.0	113.2	73.2	0.0							
30.10	4.166	0.000	105.6	119.8	113.3	114.7	117.0	129.8	120.9	85.5	75.8	0.0						
37.40	4.151	0.000	107.3	121.6	115.8	117.6	119.9	133.8	124.9	92.3	87.2	67.1	0.0					
46.20	4.127	0.000	110.4	124.4	118.4	120.6	123.1	137.6	130.1	100.4	98.7	83.8	55.2	0.0				
52.60	4.111	0.000	112.9	126.7	121.0	123.2	126.3	141.2	134.1	105.3	104.8	91.8	67.2	52.6	0.0			
62.30	4.110	0.000	114.2	128.3	123.5	125.7	128.4	144.1	137.6	110.0	111.1	100.2	77.6	68.2	67.8	0.0		
70.80	2.034	0.000	93.7	106.0	103.0	108.3	111.6	132.9	130.5	107.9	111.8	102.5	80.7	74.0	78.1	53.1	0.0	
79.90	2.268	0.000	96.9	111.3	106.5	106.9	111.6	129.4	121.9	97.6	101.2	87.0	72.5	64.2	70.5	49.9	60.0	0.0
80.00	0.000	0.000	96.4	110.8	106.1	106.8	111.4	129.3	121.9	97.8	101.2	86.8	72.6	64.8	71.1	49.5	60.3	1.7
90.00	0.000	0.000	69.5	84.3	80.4	85.3	90.8	112.3	111.1	89.8	97.5	92.4	76.8	75.8	85.6	72.7	78.8	66.4
100.00	0.000	0.000	56.4	70.7	66.9	71.4	76.7	98.3	97.4	76.9	84.7	81.5	67.5	69.4	81.4	71.8	77.7	70.1
110.00	0.000	0.000	48.0	62.5	57.7	62.5	67.0	88.4	88.0	68.5	76.4	73.8	61.9	65.0	78.4	70.4	76.8	68.2
120.00	0.000	0.000	36.8	51.5	47.5	52.8	58.0	80.8	80.9	61.2	70.0	67.4	55.2	58.3	71.7	62.2	69.2	60.9
130.00	0.000	0.000	30.0	44.1	40.8	45.5	50.5	72.6	72.5	52.9	62.2	59.5	47.6	51.3	65.1	58.1	62.6	54.5
140.00	0.000	0.000	25.1	39.4	35.7	40.4	45.1	67.3	66.3	47.3	56.4	51.5	43.4	43.4	56.4	47.3	55.9	47.6
150.00	0.000	0.000	19.5	34.3	30.3	34.9	39.5	60.9	60.1	39.2	46.9	44.3	30.9	33.4	46.2	36.3	43.3	35.0
160.00	0.000	0.000	10.3	26.1	21.9	27.2	32.4	54.5	54.0	31.5	38.8	36.1	22.7	22.9	38.7	22.9	27.3	19.6
170.00	0.000	0.000	0.0	20.0	14.4	20.5	25.5	47.6	48.1	25.7	31.6	29.2	18.4	9.4	26.8	9.4	11.2	7.9
180.00	0.000	0.000	0.0	13.0	3.2	14.4	18.5	41.5	43.7	18.1	21.6	19.7	5.8	1.8	14.9	0.0	0.0	2.5
190.00	0.000	0.000	0.0	3.4	0.0	8.1	12.6	34.6	35.8	8.5	9.3	2.3	0.0	0.0	0.0	0.0	0.0	0.0
200.00	0.000	0.000	0.0	0.0	0.0	.6	5.4	25.0	27.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
210.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	14.8	20.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
217.20	0.000	0.000	0.0	0.0	0.0	0.0	0.0	7.4	16.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 49.40 MM M2/M/M
DRAINBACK VOLUME = .05 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 3.725 L/S
INFLOW TIME = 79.50 MIN
AVE. SLOPE = .00002 M/M
AVE. TOP WIDTH A = 37.105
AVE. TOP WIDTH B = .549
AVE. WET PERIM A = 36.882
AVE. WET PERIM B = .558
AVE. SHAPE PROF = .337
AVE. SHAPE DEPTH = .282
AVE. SHAPE ADVAN = .758

Table 53. Water surface profile data for Test Number 152, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 152

NO. STA	NO. TIME PERIODS	FURROW SPACING
8	26	1.016

		STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8
DISTANCE, M		0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0
ELEVATIONS, MM		24.83	36.26	9.45	2.09	0.00	16.70	4.88	1.90
*****TOP WIDTH*******									
	R^2	.981	.934	.988	.994	.923	.919	.967	.873
*TW=A(D)^B *	A	49.362	51.506	17.874	27.540	34.364	47.248	34.314	29.930
TW & D, MM	B	.511	.516	.683	.604	.556	.511	.550	.591
*****WETTED PER******									
	R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B *	A	49.306	51.414	17.852	27.406	34.192	47.074	34.146	29.834
WP & D, MM	B	.516	.521	.697	.616	.566	.518	.560	.600
SURF. SHAPE FACT.									
*PROFILE	*	0.000	.109	.067	.091	.147	.767	.742	.459
*DEPTH	*	-.051	.118	.073	.099	.161	.272	.312	.177
*ADVANCE	*	1.089	1.089	1.089	1.089	1.089	.354	.420	.634

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM							
0.00	0.000	0.000	0.0							
.10	3.762	0.000	3.6	0.0						
.19	4.110	0.000	6.8	4.1	0.0					
.35	4.110	0.000	12.9	7.7	11.3	0.0				
.51	4.110	0.000	18.8	11.2	16.4	15.5	0.0			
2.85	4.110	0.000	86.0	54.1	82.5	80.6	69.5	0.0		
8.95	4.110	0.000	81.3	62.3	89.6	90.9	84.7	63.7	0.0	
17.75	4.110	0.000	74.6	66.4	92.7	94.7	98.2	79.5	75.9	0.0
20.00	0.000	0.000	72.9	63.7	90.6	92.7	95.0	79.8	81.9	62.9
30.00	0.000	0.000	65.5	47.5	76.4	79.5	77.2	70.0	85.2	87.5
40.00	0.000	0.000	58.8	41.0	63.7	73.1	72.4	63.6	80.9	82.5
50.00	0.000	0.000	52.8	35.7	63.6	67.5	65.8	56.8	72.4	73.3
60.00	0.000	0.000	47.5	31.1	58.9	63.0	61.7	52.7	68.8	69.9
70.00	0.000	0.000	42.7	26.8	54.5	58.7	57.5	49.1	65.3	66.3
80.00	0.000	0.000	38.3	22.7	50.5	54.7	53.7	45.3	61.8	61.5
90.00	0.000	0.000	33.9	18.6	46.5	50.5	48.9	40.2	55.1	55.8
100.00	0.000	0.000	29.4	14.6	42.5	46.2	45.3	37.3	53.7	54.1
110.00	0.000	0.000	24.7	10.8	38.6	42.4	41.4	33.3	49.5	50.6
120.00	0.000	0.000	19.6	6.4	34.4	38.7	37.6	28.9	44.2	46.1
130.00	0.000	0.000	14.2	1.6	29.9	33.7	32.4	24.1	39.1	40.2
140.00	0.000	0.000	8.4	0.0	25.8	29.6	28.8	19.8	34.4	36.3
150.00	0.000	0.000	2.5	0.0	21.1	25.0	23.8	14.5	29.5	32.2
160.00	0.000	0.000	0.0	0.0	15.8	19.6	18.5	6.9	24.1	27.9
170.00	0.000	0.000	0.0	0.0	9.3	13.0	13.4	0.0	17.6	22.2
180.00	0.000	0.000	0.0	0.0	1.4	4.3	5.4	0.0	7.8	16.7
186.00	0.000	0.000	0.0	0.0	0.0	0.0	.4	0.0	2.0	12.6

INFLOW VOLUME = 38.82 MM M2/M/M
DRAINBACK VOLUME = .06 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.108 L/S
INFLOW TIME = 19.20 MIN
AVE. SLOPE = -.00015 M/M
AVE. TOP WIDTH A = 35.648
AVE. TOP WIDTH B = .560
AVE. WET PERIM A = 35.440
AVE. WET PERIM B = .570
AVE. SHAPE PROF = .275
AVE. SHAPE DEPTH = .145
AVE. SHAPE ADVAN = .567

Table 54. Water surface profile data for Test Number 153, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 153

NO. STA	NO. TIME PERIODS	FURROW SPACING
12	31	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
ELEVATIONS, MM	39.69	30.85	23.27	18.85	18.20	22.61	35.50	24.73	26.50	22.86	20.61	0.00
*****TOP WIDTH*******												
R^2	.987	.987	.983	.986	.989	.995	.906	.952	.993	.962	.991	.988
*TW=A(D)^B * A	34.978	44.156	29.864	33.426	16.390	24.424	43.908	4.778	12.690	14.906	18.732	31.904
TW & D, MM B	.572	.520	.585	.567	.729	.629	.504	.955	.767	.731	.679	.586
*****WETTED PER******												
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	34.918	44.038	29.770	33.316	16.438	24.378	43.748	5.178	12.788	14.958	18.722	31.816
WP & D, MM B	.579	.526	.595	.576	.740	.639	.512	.963	.780	.744	.692	.594
SURF. SHAPE FACT.												
*PROFILE *	.149	.138	.130	.128	.144	.562	.376	.486	.880	.398	.880	.244
*DEPTH *	.193	.179	.169	.166	.187	.279	.392	.272	.467	.378	.417	.317
*ADVANCE *	1.298	1.298	1.298	1.298	1.298	.497	1.016	.560	.531	.950	.474	.908

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM											
0.00	0.000	0.000	0.0											
.55	4.048	0.000	10.1	0.0										
.93	4.110	0.000	17.2	23.9	0.0									
1.59	4.110	0.000	29.3	40.8	41.4	0.0								
2.17	4.110	0.000	40.1	55.8	56.5	52.8	0.0							
4.15	4.110	0.000	66.7	78.0	81.2	79.4	71.9	0.0						
9.38	4.110	0.000	77.2	92.5	97.1	97.6	96.1	74.4	0.0					
12.45	4.110	0.000	82.6	97.6	102.7	103.5	103.0	86.2	50.8	0.0				
18.55	4.110	0.000	90.5	106.0	110.7	112.7	113.0	100.8	84.4	68.3	0.0			
26.15	4.110	0.000	94.3	111.7	116.6	118.3	120.1	109.5	99.2	87.9	59.0	0.0		
30.75	4.110	0.000	95.4	114.6	119.5	121.5	123.4	114.1	104.7	96.1	74.6	51.7	0.0	
40.75	3.878	0.000	93.1	111.4	114.5	117.8	122.4	114.2	110.1	103.3	90.3	79.1	57.8	0.0
50.00	0.000	0.000	67.4	83.9	89.7	93.2	96.3	94.9	96.0	98.8	90.2	88.1	77.9	82.9
60.00	0.000	0.000	59.4	75.7	81.5	84.5	88.0	85.7	86.8	90.7	83.9	81.5	78.5	84.3
70.00	0.000	0.000	54.1	70.5	76.3	79.5	83.1	81.2	83.9	84.4	79.4	81.1	74.1	81.9
80.00	0.000	0.000	48.6	64.8	70.7	74.0	77.0	75.4	76.0	77.8	70.2	68.9	64.1	68.3
90.00	0.000	0.000	44.0	60.2	65.9	69.3	73.0	70.2	71.1	72.6	64.9	64.5	58.6	63.9
100.00	0.000	0.000	39.0	55.3	61.2	64.8	68.4	66.1	68.0	69.2	62.9	63.0	56.4	62.5
110.00	0.000	0.000	34.5	51.0	56.7	59.7	63.3	61.2	64.0	65.5	59.7	59.9	52.3	58.1
120.00	0.000	0.000	30.0	46.5	52.6	55.2	58.7	57.0	58.1	60.4	53.2	50.3	45.5	49.8
130.00	0.000	0.000	25.9	42.2	48.3	50.5	53.7	51.9	53.9	54.9	50.6	49.2	42.0	46.1
140.00	0.000	0.000	21.4	38.0	43.6	46.6	50.4	47.1	49.0	50.6	48.5	45.2	38.7	45.2
150.00	0.000	0.000	15.4	31.9	37.8	41.3	45.0	43.1	44.9	46.6	40.2	39.8	32.9	40.0
160.00	0.000	0.000	10.5	26.8	32.7	36.5	39.9	37.9	39.8	42.1	33.6	34.4	26.6	32.8
170.00	0.000	0.000	5.8	22.5	28.8	32.1	35.5	33.4	35.8	37.1	28.8	27.3	20.0	24.8
180.00	0.000	0.000	1.7	17.5	23.6	26.8	30.5	27.6	29.2	30.7	22.2	19.3	10.8	16.3
190.00	0.000	0.000	0.0	12.2	18.4	21.5	25.3	22.1	22.9	23.5	13.9	10.0	.5	5.4
200.00	0.000	0.000	0.0	5.6	11.9	15.2	19.9	15.0	15.6	16.5	4.1	.1	0.0	0.0
210.00	0.000	0.000	0.0	0.0	4.1	7.3	13.8	6.4	8.6	10.6	0.0	0.0	0.0	0.0
220.00	0.000	0.000	0.0	0.0	0.0	0.0	6.6	0.0	3.7	6.4	0.0	0.0	0.0	0.0
228.60	0.000	0.000	0.0	0.0	0.0	0.0	1.3	0.0	.1	2.2	0.0	0.0	0.0	0.0

INFLOW VOLUME = 40.63 MM M2/M/M
DRAINBACK VOLUME = .05 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.109 L/S
INFLOW TIME = 40.18 MIN
AVE. SLOPE = -.00006 M/M
AVE. TOP WIDTH A = 23.351
AVE. TOP WIDTH B = .642
AVE. WET PERIM A = 23.216
AVE. WET PERIM B = .654
AVE. SHAPE PROF = .388
AVE. SHAPE DEPTH = .284
AVE. SHAPE ADVAN = .861

Table 55. Water surface profile data for Test Number 154, Table 1.

MAC FURROW DRAINBACK STUDY NUMBER 154

NO. STA	NO. TIME PERIODS	FURROW SPACING
16	34	1.016

	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA10	STA11	STA12	STA13	STA14	STA15	STA16
DISTANCE, M	0.0	5.0	10.0	20.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	354.0
ELEVATIONS, MM	22.42	12.07	16.71	9.51	1.56	0.00	.64	22.98	11.89	7.75	23.44	17.08	10.17	19.58	8.94	18.73
*****TOP WIDTH*******																
R^2	.934	.933	.957	.894	.954	.934	.988	.946	.934	.978	.942	.976	.991	.998	.985	.967
*TW=A(D)^B * A	71.390	50.234	62.938	26.100	31.044	19.704	25.088	45.340	29.616	57.152	66.616	49.688	39.844	27.830	18.278	19.430
TW & D, MM B	.432	.478	.432	.627	.586	.673	.629	.512	.596	.456	.423	.491	.528	.612	.705	.682
****WETTED PER******																
R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
*WP=A(D)^B * A	71.270	50.070	62.729	26.072	30.954	19.698	25.032	45.196	29.538	56.834	66.310	49.522	39.694	27.759	18.295	19.444
WP & D, MM B	.436	.485	.438	.636	.595	.685	.639	.519	.605	.463	.430	.498	.537	.622	.716	.692
SURF. SHAPE FACT.																
*PROFILE *	.147	.219	.203	.217	.185	.279	.248	1.000	.677	.598	.415	.852	.714	.606	1.000	0.000
*DEPTH *	.104	.155	.144	.153	.131	.197	.197	.593	.454	.462	.338	.493	.446	.400	.731	.642
*ADVANCE *	.706	.706	.706	.706	.706	.707	.794	.537	.670	.786	.815	.579	.624	.660	.713	0.000

TIME MIN	Q IN L/S	Q OUT L/S	HEAD MM															
0.00	0.000	0.000	0.0															
.24	3.913	0.000	56.9	0.0														
.64	4.053	0.000	61.6	53.1	0.0													
1.71	4.053	0.000	68.0	64.0	32.8	0.0												
3.04	4.053	0.000	76.0	77.5	67.4	60.6	0.0											
5.55	4.053	0.000	83.1	94.8	83.5	80.2	76.8	0.0										
9.85	4.053	0.000	86.2	93.4	92.1	91.6	91.9	88.4	0.0									
14.15	4.053	0.000	90.9	104.2	97.8	97.7	93.0	103.9	85.5	0.0								
21.45	4.053	0.000	97.0	110.4	104.6	105.6	107.6	118.4	104.9	56.1	0.0							
28.15	4.053	0.000	101.4	114.3	108.8	109.8	112.7	125.8	116.6	81.4	65.8	0.0						
34.25	4.053	0.000	103.1	117.0	110.9	112.7	115.5	130.1	122.1	91.2	85.7	52.7	0.0					
40.35	4.053	0.000	105.3	119.1	113.5	115.2	118.8	133.5	125.3	96.0	93.3	73.8	39.6	0.0				
49.45	4.053	0.000	108.4	122.0	116.6	118.3	121.3	136.9	129.2	101.0	100.2	89.4	58.3	37.5	0.0			
58.55	4.053	0.000	111.0	124.9	119.6	122.1	125.1	141.1	134.8	107.3	109.3	98.2	72.3	57.3	53.0	0.0		
67.65	4.053	0.000	112.6	126.5	121.0	123.4	126.5	142.0	137.5	110.8	112.0	102.5	80.8	71.5	74.8	46.5	0.0	
74.65	4.053	0.000	111.2	124.2	120.3	123.8	126.8	143.0	136.1	110.2	113.5	104.5	84.2	78.4	85.4	62.4	39.2	0.0
80.00	0.000	0.000	93.3	107.9	101.7	106.6	111.2	132.5	130.2	106.7	113.3	104.9	85.1	81.6	90.8	72.5	61.7	45.1
90.00	0.000	0.000	73.3	87.0	83.1	86.9	91.5	112.5	113.0	93.2	100.2	97.6	82.8	82.8	95.0	83.4	87.2	80.6
100.00	0.000	0.000	61.3	75.4	71.2	75.0	73.9	101.9	101.5	82.7	92.8	90.9	77.0	78.9	92.5	85.1	92.6	88.1
110.00	0.000	0.000	53.9	68.0	63.7	67.6	72.2	93.5	93.4	74.2	83.8	81.6	68.8	71.7	83.8	75.2	82.6	72.6
120.00	0.000	0.000	47.0	61.1	56.8	60.6	65.5	86.1	85.6	66.3	74.7	71.3	60.9	64.1	75.1	65.4	72.0	60.6
130.00	0.000	0.000	40.6	54.9	50.7	54.3	59.8	81.2	80.3	61.1	71.7	65.6	54.9	57.9	70.1	61.4	66.9	53.6
140.00	0.000	0.000	34.1	48.3	43.9	47.5	52.4	74.3	73.5	54.6	64.4	62.0	49.6	52.3	65.3	56.3	61.3	55.0
150.00	0.000	0.000	27.9	42.0	37.7	41.4	46.0	68.4	67.7	47.9	57.8	56.3	43.8	46.3	59.0	47.7	53.2	44.4
160.00	0.000	0.000	22.6	36.7	32.0	35.5	40.1	61.9	60.5	40.2	48.5	50.1	37.4	39.6	53.4	41.0	46.3	35.8
170.00	0.000	0.000	17.2	31.0	25.9	30.0	34.8	53.2	53.9	33.3	40.5	43.3	30.0	31.4	47.0	36.5	41.1	36.2
180.00	0.000	0.000	10.4	25.3	19.9	23.7	28.1	49.4	48.4	27.1	35.6	33.9	20.7	20.8	36.3	24.2	28.9	26.3
190.00	0.000	0.000	.9	19.4	13.4	17.1	21.9	42.0	41.4	18.6	25.3	23.3	9.8	8.8	23.5	5.9	10.2	12.5
200.00	0.000	0.000	0.0	11.9	3.9	11.2	15.9	36.8	35.8	10.4	15.9	9.9	0.0	0.0	10.7	0.0	0.0	5.0
210.00	0.000	0.000	0.0	2.0	0.0	4.5	10.0	28.3	23.3	1.8	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
220.00	0.000	0.000	0.0	0.0	0.0	0.0	3.0	19.0	21.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
230.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	5.2	12.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
240.00	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
243.60	0.000	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INFLOW VOLUME = 51.22 MM M2/M/M
DRAINBACK VOLUME = .09 MM M2/M/M
RUNOFF VOLUME = 0.00 MM M2/M/M
AVE. INFLOW RATE = 4.053 L/S
INFLOW TIME = 75.77 MIN
AVE. SLOPE = .00002 M/M
AVE. TOP WIDTH A = 37.105
AVE. TOP WIDTH B = .549
AVE. WET PERIM A = 36.882
AVE. WET PERIM B = .558
AVE. SHAPE PROF = .490
AVE. SHAPE DEPTH = .356
AVE. SHAPE ADVAN = .755

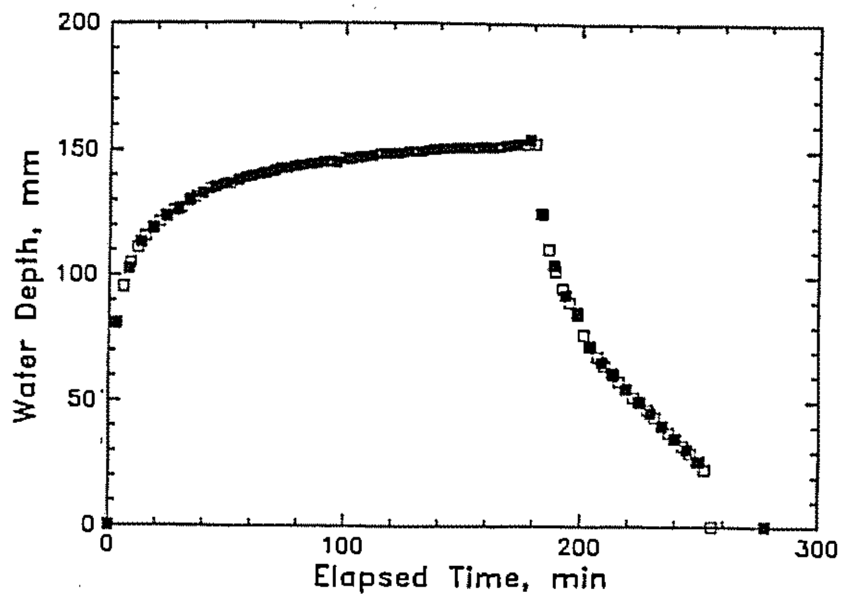

Fig. 1. Hydrograph for furrow station 20 meters from the inlet end of the level furrow used for Test Number 103, Table 1. The water depth measurements were developed from bubbler/pressure transducer readings (open symbols). The solid symbols represent smoothed data and were used to replace the original data.

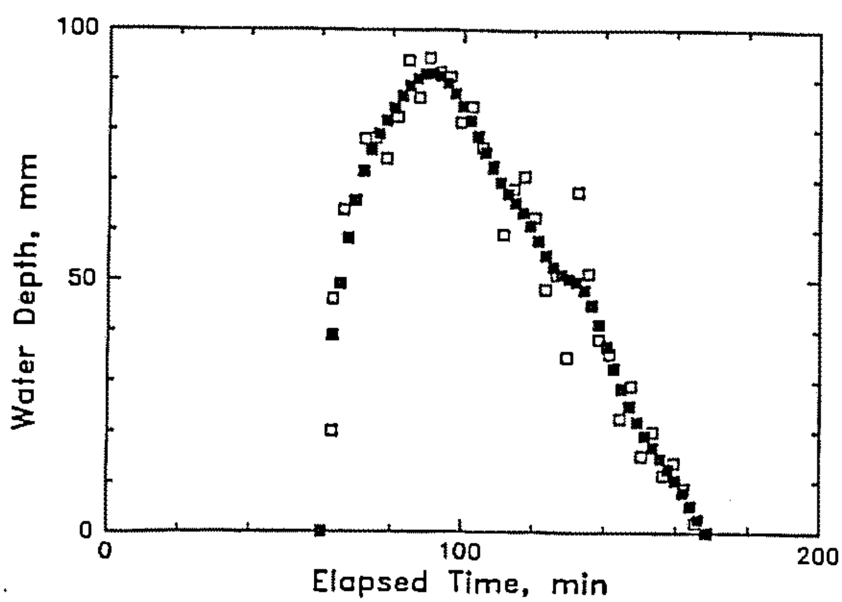

Fig. 2 Hydrograph for furrow station 300 meters from the inlet end of the level furrow used for Test Number 115, Table 1. Open symbols represent original data while the solid symbols represent smoothed data and were used to replace the original data.

TITLE: SOIL-PLANT-ATMOSPHERE INTERACTIONS AS RELATED TO WATER CONSERVATION AND CROP PRODUCTIVITY

SPC: 6.1.03.1.c (70%)
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INTRODUCTION

Another banner year for publications for our research group with 29 manuscripts published, 31 in press, and 14 in journal review process. Those reported below in abstract form represent some of the most interesting. Additionally, a few experiments were conducted during the year and are reported here before manuscripts have been prepared.

Four papers dealing with the energy balance at the earth's surface all have a common theme. That is, remotely sensed, emitted and reflected radiation combined with a few simple ground-based micrometeorological measurements allow the calculation of evapotranspiration (ET) from agricultural fields and from native vegetation. These calculations agree well with Bowen ratio measurements of ET. Reflectance measurements are the subject of six manuscripts. One paper considered atmospheric influences on the Thematic Mapper spectra of partial canopies of cotton and grass, and concluded that the turbidity of the atmosphere were significantly dependent on the 'brightness' of the underlying soil. A second paper compared SPOT-1 satellite data, corrected for atmospheric effects, with data obtained from low-level aircraft and ground-based observations, and found that a simple view angle correction to the satellite reduced the absolute reflectance errors by 50% over rough surfaces. Alfalfa biomass was estimated spectrally under variable cloud conditions in a third paper, and it was found that plant growth can be quantified even when direct beam solar irradiances are not constant. A fourth paper considered the influence of topography and sensor view angles on vegetation indices. It was shown that the NIR/red ratio was less sensitive to field aspect than greenness, but the reverse was true when nadir and off-nadir view angles were compared for the same aspect. The last two papers dealing with reflectance discussed techniques that could be used for the in-flight calibration of satellite sensors.

Two papers dealt with the crop water stress index (CWSI). The first reexamined the theoretically-developed CWSI and proposed a method for estimating an aerodynamic resistance applicable to a plant canopy. A second paper was a review of the general topic of assessing crop stress for the purpose of scheduling irrigations. Evaporation from water surfaces and aquatic macrophytes was the subject of four manuscripts. Two of the papers considered the role of stomates for controlling water loss from these types of plants, while the other two papers presented information on the effect of fractional plant cover on the evaporation from water surfaces. A recent controversy has arisen concerning the validity of measurements made with commercial diffusion porometers. Three papers address this topic and present methods to correct porometer readings.

The effect of atmospheric carbon dioxide on plant growth is a subject of six papers. Several years of research on seven different plants (five terrestrial and two aquatic species) have demonstrated several things. First is the fact that the stimulatory effect of atmospheric carbon dioxide enrichment is strongly temperature dependent. Next, it was shown that the enrichment has little effect on plant percent dry matter, except under conditions conducive to starch accumulation in leaves, and then it caused an increase in percent dry matter content. It was also proposed that the beneficial effects of carbon dioxide may be divided into three distinct growth response phases. Also, it was suggested the carbon dioxide effects on worldwide vegetative productivity have been demonstrated.

Climatic consequences of increasing atmospheric carbon dioxide are noted in five manuscripts. One attributes the long term global temperature trend to the natural recovery of the Earth from the global chill of the Little Ice Age rather than increasing atmospheric carbon dioxide. Another explores the reasons for predictions of a "nuclear winter (or fall)," and disputes the analysis made by climate modelers. Along this same line, is a discussion of the effects of large volcanic explosions on global climate. The other two manuscripts review other aspects of the carbon dioxide-climate issue.

Wheat is the topic of two papers, but their contents are quite different. The first is an introductory paper to seven others describing an experiment conducted in the North American Great Plains from Texas to Canada to study the response of wheat to water and nitrogen. The second paper describes how canopy temperature might be used to screen wheat cultivars for their ability to withstand drought. Over the past nearly 30 years there has been an on-going project on the use of neutron attenuation equipment to assess soil water content. One paper describes a unique calibration transfer procedure using plastic cylinders.

In addition to manuscripts that have been or are in the process of being published, a few mini-experiments have been conducted and are reported herein. The first deals with a comparison of blackbody calibration devices used to check the reliability of infrared thermometers (IRT). It was concluded that these portable devices perform quite well for general field use, and confirms the practice of comparing the readings from an IRT and the blackbody before and after measuring surface temperatures in the field to insure the integrity of the data. A second experiment, called MACII, was a multi-organizational effort (1) to assess the spatial and temporal distribution of ET over several agricultural fields (2) to assess the potential of using bare soil surfaces of different roughnesses to evaluate atmospheric models for interpreting aircraft and satellite data, and (3) to investigate the possibility of calculating aerodynamic resistance over partial canopy cover. The unique part of this experiment was that the 27 participants, representing seven departments from five universities, six offices from three federal agencies, two private institutions and one foreign national agency, were funded by their respective organizations. Preliminary results from two parts of that experiment was reported herein: emissivity determinations of plants and soils and ground-based reflectance measurements over cropped and bare soil surfaces.

ENERGY BALANCE

Jackson, R.D. Surface temperature and the surface energy balance. IN: Proc. Intern. Symp. on Flow & Transport in the Natural Environment: Advances and Applications. Canberra, Australia, Sept. 1987. (in press)

Surface temperatures, determined from measurements of emitted radiation, can be obtained at scales ranging from a few mm^2 to the global hemisphere. The ability to measure temperatures over large areas has led to the development of techniques for evaluating the surface energy balance at regional scales. In addition to surface temperatures, some techniques require inputs of surface-measured meteorological parameters. Others model the surface fluxes and use a comparison of predicted and measured surface temperatures to keep the models on track. Because of the large scale, validation of the models is difficult. On a smaller scale, it is possible to use both remotely-sensed data and ground-based data to evaluate the energy balance, with validation being somewhat easier. In this review, both regional- and local-scale techniques are discussed. An experiment in which remotely-derived results were compared with Bowen ratio data is described in detail. It is shown that the remote technique will produce adequate values of latent heat flux for uniform surfaces, but may yield erroneous values for heterogeneous surfaces such as partial canopies.

Raymond, L.H., Moran, M.S. and Jackson, R.D. Mapping latent heat energy from remotely sensed data and other variables using ARC/INFO software. IN: Proc. Spatial Data System for Management, University of Arizona, Tucson, AZ. 5-6 Nov. 1987. pp. 38-45.

Latent heat energy calculated with an energy budget using remotely sensed data from the Landsat-5 Thematic Mapper (TM) and from aircraft were compared with crop type, crop density, soil type, and available soil moisture using ARC/INFO geographical information system software. Latent heat energy calculated from the TM data was within 12 percent of latent heat energy calculated from the aircraft data 88 percent of the time. Latent heat energy was most closely related to soil moisture and somewhat related to crop type and crop density. Soil type was most closely related to spectral reflectance of the ground surface.

Reginato, R.J. and Jackson, R.D. Remote sensing of water use by agricultural crops and natural vegetation. IN: Proc. USCID Regional Meeting on Water Management. Denver, CO. 2-4 Sept. 1987 (in press)

Water loss from soil and vegetation was evaluated from agricultural crops and an arid ecosystem using a combination of remotely sensed and ground-based data. This information was used in the energy balance equation, and eddy correlation systems. An analysis demonstrated that when the vegetation cover was near complete, calculations of evapotranspiration (ET) agreed well with field data, but when the vegetation was sparse, the agreement was poor. Empirically derived coefficients, based on fractional plant cover and plant height brought the results of the two techniques closer together. The data demonstrate the shortcomings of the theoretical approach in estimating ET over areas of partial vegetation, and where additional research is needed in order to solve the problems. Before remote sensing techniques can be used confidently over large areas to estimate ET, existing theory must be modified or new theory developed.

Reginato, R.J. Surface energy flux measurements and reflectance factors using satellite-, aircraft-, and ground-based instrumentation. IN: Proc. ERIM Symp., Ann Arbor, MI. 26-30 Oct. 1987. (in press)

Knowledge of the type and amount of vegetation covering agricultural fields and the amount of evapotranspiration from those surfaces will greatly assist farm supervisors in managing their water resources more efficiently. For timely management decisions, it is necessary to make these assessments quickly over large areas, and remote sensing technology offers a solution. To evaluate the accuracy of these types of measurements, a week-long field experiment was conducted in June 1987 to assess the energy flux and spectral reflectance distribution both spatially and temporally over several agricultural fields. The energy flux components of interest were latent heat (evapotranspiration) and sensible heat. These wee evaluated at ground level with four Bowen ratio systems, with four eddy correlation units, and with a tethered balloon radiosonde system. Also, four-band and eight-band radiometers along with appropriate micrometeorological data were used to estimate fluxes. Radiometers were mounted in an aircraft to measure reflected and emitted radiation from selected agricultural fields. Landsat TM data were scheduled but not obtained due to clouds. SPOT data were obtained on two successive days. Atmospheric optical depth measurements allowed satellite based reflectance factor data to be compared with aircraft and ground-based reflectance factors for bare soil and agricultural crops. The 27 participants, who represented seven departments from five universities, six offices from three federal agencies, two private institutions and one foreign agency were funded by their respective organizations for their part in the overall experiment.

SPECTRAL REFLECTANCE

Huete, A.R. and Jackson, R.D. Soil and atmosphere influences on the spectra of partial canopies. Remote Sensing Environ. (in press)

An atmospheric radiant transfer model was used to compare ground measured radiances over partially vegetated canopies with those observable at the top of a clear (100 km meteorological range) and a turbid (10 km) atmosphere. Radiance measurements in the first four bands of the

Thematic Mapper were taken over incomplete cotton (Gossypium hirsutum L.) and Lehmann lovegrass (Eragrostis lehmanniana) canopies with different soil backgrounds separately inserted underneath.

Atmospheric influences on the spectra of partial canopies were found to be significantly dependent on the 'brightness' of the underlying soil. The change in canopy red and near-infrared radiant flux between the ground and the top of the atmosphere was such that an increase, decrease or no change could be observed depending on the magnitude of the soil spectral contribution. Both increasing soil 'brightness' and atmospheric turbidity lowered the ratio and normalized difference vegetation index values. Consequently atmospheric-induced RVI and NDVI degradation were greatest over canopies with darker soils and were not detectable over canopies with light colored soils. In contrast, soil and atmospheric effects on the perpendicular vegetation index were independent with atmosphere degradation being similar across all soil backgrounds. Soil influences on partial canopy vegetation indices were found to be of similar magnitude to those attributed to the atmosphere for the range of values examined here.

Moran, M.S., Jackson, R.D., Hart, G.F., Slater, P.N., Bartell, R.J., Biggar, S.F. and Santer, R.P. Surface reflectance factors derived from SPOT-1 HRV data at two view angles. IN: Proc. Intern. Conf. on the SPOT-1 Image Utilization, Assessment, Results. Paris, France, 23-27 Nov. 1987. (in press)

SPOT-1 XS and Pan data were acquired over an agricultural area on two consecutive days at view zenith angles of -10.7 and +23.0 degrees. Digital data were converted to radiance using the SPOT-1 internal calibrator coefficients. A radiative transfer model, using optical depth data measured on overpass days, was used to calculate surface reflectance factors from the radiances. Satellite-derived surface reflectance factors (Rs) were compared with reflectance factors measured at ground level and from low-altitude aircraft (Rg and Ra, respectively). Differences between Rs, Rg and Ra at the same view zenith angle and solar zenith angle over bare soil were less than 0.014 reflectance for all XS bands on both days. A simple view angle correction was computed from ground-based measurements of radiance from bare soil at numerous view angles. Rs values over rough surfaces, i.e., bare soil, orchards and full cover crops, that had originally differed by over 0.09 absolute reflectance on the two days were brought to within 0.005 difference in all three XS bands. The correction overcompensated for view angle effects over planar surfaces, i.e., water and roads.

Pinter, P.J., Jr., Kelly, H.L., Jr. and Schnell, S. Spectral estimation of alfalfa biomass under conditions of variable cloud cover. IN: Proc. 18th AMS Conf. on Agriculture and Forest Meteorology, Purdue University, W. Lafayette, IN. 13-18 Sept. 1987. pp. 83-86.

A field experiment was conducted at Phoenix, AZ to examine the effect of water stress on reflectance characteristics of an alfalfa crop. Multispectral observations were made using an Exotech hand-held radiometer equipped with bandpass filters similar to the multispectral scanner on board Landsat-5. Data were collected each morning at a constant solar zenith angle of 57 regardless of sky or cloud conditions. Results showed a significant correlation between biomass and several vegetation indices (VIs) calculated from red and near-infrared reflectance factors. Analysis of data collected under clear sky, partly cloudy and completely overcast conditions revealed that VIs computed as ratios of NIR and Red reflectance factors were less sensitive to cloud cover than single band reflectances or linear band combinations such as Greenness. These findings suggest that ground-based remote sensing approaches for quantifying plant growth are useful even during conditions when direct beam solar irradiances are not constant.

Pinter, P.J., Jr., Zipoli, G., Maracchi, G. and Reginato, R.J. Influence of topography and sensor view angles on NIR/red ratio and greenness vegetation indices of wheat. Intern. J. Remote Sensing 8:953-957. 1987.

Reflectance factors of winter wheat were measured with a ground-based radiometer to determine the effect of topography and sensor view angle on the diurnal behavior of two spectral vegetation indices. Data are presented for fields with 10° slopes in a topographical complex area of central Italy. The ratio of reflectances in near-infrared (NIR) (0.78 to 0.89 μm) to red (0.63 to 0.69 μm) was less sensitive to field aspect than greenness. However, when nadir and off-nadir view angles were compared for the same aspect, greenness displayed less variability. Field aspect and view angle had less effect on both indices when solar zenith angles were small.

Slater, P.N., Biggar, S.F., Holm, R.G., Jackson, R.D., Mao, Y., Moran, M.S., Palmer, J.M. and Yuan, B. Reflectance- and radiance-based methods for the inflight absolute calibration of multispectral sensors. Remote Sensing Environ. 22:11-37. 1987.

Variations reported in the in-flight absolute radiometric calibration of the Coastal Zone Color Scanner (CZCS) and the Thematic Mapper (TM) on Landsat-4 are reviewed. At short wavelengths these sensors exhibited a gradual reduction in response, while in the mid-infrared the TM showed oscillatory variations.

The methodology and results are presented for five reflectance-based calibrations of the Landsat-5 TM at White Sands, New Mexico, in the period July 1984 to November 1985. These show a ±2.8% standard deviation (1 sigma) for the six solar reflective bands.

Analysis and preliminary results of a second, independent calibration method based on radiance measurements from a helicopter at White Sands indicate that this is potentially an accurate method for corroborating the results from the reflectance-based method.

Teillet, P.M., Slater, P.N., Jackson, R.D., Fedosejevs, G. and Moran, M.S. Reflectance measurements at White Sands, New Mexico, using a mobile spectroscopy laboratory. IN: Proc. Eleventh Canadian Symp. on Remote Sensing. Waterloo, Ontario, Canada, 22-25 June 1987. (in press)

A promising approach to the in-orbit calibration of satellite sensors is the use of special ground targets such as the gypsum flats of White Sands, New Mexico. A key aspect of the White Sands effort has been to measure the ground reflectance in spectral bandpasses and response profiles corresponding to those of the satellite sensor of interest. With a view to examining different ways of going about these ground reflectance measurements and also to becoming more actively involved in satellite calibration research internationally, the Canada Centre for Remote Sensing (CCRS) accepted the University of Arizona's invitation to deploy the CCRS mobile spectroscopy laboratory at White Sands during the winter of 1985/86. Spectra of the gypsum surface were acquired in a variety of configurations during LANDSAT TM and SPOT HRV overpasses. The spectral measurement activities and resulting data sets are described. Advantages and disadvantages of using a mobile spectroscopy facility for this type of work are discussed from spectral, spatial, and temporal perspectives. Finally, the role of strategic studies and collaborative efforts at White Sands by a variety of research groups is discussed in the light of increasing interdisciplinary interest using satellite data for monitoring resources and climatological change on regional and global scales.

CROP WATER STRESS INDEX

Jackson, R.D., Kustas, W.P. and Choudhury, B.J. A reexamination of the crop water stress index. Irrigation Science. (in press)

Hand-held infrared radiometers, developed during the past decade, have extended the measurement of plant canopy temperatures from individual leaves to entire plant canopies. Canopy temperatures are determined by the water status of the plants, and ambient meteorological conditions. The crop water stress index (CWSI) combines these factors and yields a measure of plant water stress. Two forms of the index have been proposed, an empirical approach as reported by Idso *et al.* (1981), and a theoretical approach reported by Jackson *et al.* (1981). Because it is simple and requires only three variables to be measured, the empirical approach has received much attention in the literature. It has, however, received some criticism concerning its inability to account for temperature changes due to radiation and windspeed. The theoretical method is more complicated in that it requires these two additional variables to be measured, and the evaluation of an aerodynamic resistance, but it will account for differences in radiation and windspeed. This report reexamines the theoretical approach and proposes a method for estimating an aerodynamic resistance applicable to a plant canopy. A brief history of plant temperature measurements is given and the theoretical basis for the CWSI reviewed.

Reginato, R.J. Irrigation scheduling and plant water use. IN: Proc. Intern. Conf. on Agrometeorology. Cesena, Italy, 8-9 Oct. 1987. pp. 189-200.

Development of remote sensing techniques for measuring components of the energy balance at the earth's surface, show great promise for managing farm water resources. Using reflected and emitted radiation measurements coupled with routine agrometeorological information, it is possible to assess crop stress and evapotranspiration from vegetated surfaces. Methods have been developed using foliage temperature measurements to determine when plants are under stress and to quantify that stress for irrigation scheduling purposes. From reflected radiation and surface temperature data, evapotranspiration can be calculated, and, if a water budget procedure is used, the proper quantity of water needed for irrigation can be applied. A review of these techniques is presented.

EVAPOTRANSPIRATION

Idso, S.B. Development of a simplified plant stomatal resistance model and its validation for potentially-transpiring and water-stressed water hyacinth. Atmos. Environ. (in press)

A simple model of upper-canopy plant stomatal resistance (r_{uc}) was developed which requires but four input parameters: canopy aerodynamic resistance, upper-canopy foliage temperature, and air vapor pressure deficit and temperature. The model was tested against upper-canopy sunlit leaf stomatal resistance (r_L) measurements of both potentially and non-potentially transpiring water hyacinth plants over the upper-canopy-intercepted net radiation range of 300 to 450 W m^{-2} and over a ten-fold range of r_L. In all instances, and indicative of the model's good performance, the ratio of r_{uc}/r_L consistently averaged about 1.25, due to partial self-shading of the upper-canopy foliage. The significance of this finding to air pollution studies arises from the facts that 1) contemporary knowledge of a plant canopy's leaf area index would allow the transformation of r_{uc} to r_c, the total canopy diffusive resistance, and 2) the proper accounting for different trace gas diffusivities would allow the transformation of r_c for water vapor to the variety of r_c values required to infer the gaseous deposition of important pollutant gas species at vegetated surfaces.

Idso, S.B. and Anderson, M.G. A comparison of two recent studies of transpirational water loss from emergent aquatic macrophytes. Aquat. Bot., in press.

Data from two recent studies suggest that the large expanses of short water hyacinths tend to reduce the amount of water which would normally be lost by evaporation from the surfaces of sizable water bodies, but that tall water hyacinths tend to enhance evaporative water losses from such surfaces. For cattails, however, more evidence is needed before any similar conclusion may be reached.

Anderson, M.G. and Idso, S.B. Surface geometry and stomatal conductance effects on evaporation from aquatic macrophytes. Water Resour. Res. 23:1037-1042.

Evaporative water loss rates of several floating and emergent aquatic macrophytes were studied over a 4-year period through comparison of daily evaporative water losses from similar-sized vegetated (E) and open water (E_o) surfaces. Two species with planate floating leaves (water fern and water lily) yielded E/E_o values of 0.90 for one and four growing seasons, respectively, and displayed stomatal regulation of potential evaporation. Water hyacinths grown in ponds with different diameters exhibited E/E_o ratios which decreased with increasing pond diameter for both short (0.06-0.36 m) and tall (0.63-0.81 m) plants, producing high linear correlations with amount of peripheral vegetative surface area. The latter relationships suggested an E/E_o value less than unity for a relatively extensive canopy of short water hyacinths and a value of the order of 1.4 for a tall canopy possessing similar two-dimensional surface area characteristics. The latter results were also demonstrated in a separate study utilizing polyurethane foam to insulate the peripheral exposure of tall water hyacinth canopies from advective energy. Finally, simultaneous stomatal conductance and daily E/E_o measurements on cattail and water hyacinth canopies with identical tank diameters indicated that although the mean stomatal conductance of the peripheral exposure of the cattail canopy was 72% less than that of the water hyacinth canopy, its total evaporative water loss was nearly equivalent, due to its greater height. Reducing the surface area of the peripheral cattail exposure by the fractional amount suggested by the stomatal conductance measurements harmonized its surface geometry-evaporation relationship with that of the water hyacinth canopy and once again demonstrated the reality of stomatal control of potential evaporation.

Anderson, M.G. and Idso, S.B. Effects of atmospheric carbon dioxide enrichment upon the stomatal conductance and evapotranspiration of aquatic macrophytes. IN: "Aquatic Plants for Water Treatment and Resource Recovery," K.R. Reddy and W.H. Smith, eds., Magnolia Pub., Inc., Orlando, FL. pp. 421-431.

The evapotranspiration characteristics of water hyacinth, water lily, water fern, and cattail were established during a four year investigation of advective energy exchange as a function of peripheral canopy exposure and stomatal conductance. Total water loss decreased by 10% (E/E_o = 0.90) compared to an identical open water surface for water lily and water fern. Short to medium height water hyacinth displayed similar E/E_o ratios for relatively extensive surface coverages where peripheral exposure was minimal; but tall hyacinth and cattail yielded E/E_o values near 1.45. Steady-state porometer measurements indicated a 50% reduction in stomatal conductance with a 20% decrease in transpiration per unit leaf area for a mean doubling of ambient CO_2 levels. Water hyacinth biomass production increased by 36% and water use efficiency doubled for a similar doubling of the atmospheric CO_2 content. The combination of he studies indicates that floating or emergent species with leaves near the water surface will experience decreased transpiration in future higher CO_2 atmospheres, while substantial biomass increases on the taller floating or emergent species will provide greater surface exposure and possibly result in equivalent transpiration.

POROMETRY

Idso, S.B. An apparent discrepancy between porometry and infrared thermometry relative to the dependence of plant stomatal conductance on air vapor pressure deficit. Agric. For. Meteorol. 40:105-106.

Many porometry studies of a host of different plant species suggest that, as the vapor pressure deficit of the air increases, the stomatal conductances of the plants' leaves decrease. This effect, however, is in conflict with the results of infrared thermometry assessments of foliage temperatures in the free-air environment. It is suggested, therefore, that the porometry measurements may have some unknown problem associated with them.

Idso, S.B., Allen, S.G. and Choudhury, B.J. Problems with porometry: Measuring stomatal conductances of potentially transpiring plants. Agric. For. Meteorol. (in press)

Porometer measurements of the stomatal conductances (C_s) of potentially-transpiring water hyacinth plants at Phoenix, Arizona in October of 1984, May-June of 1985, and September of 1986 indicate that C_s steadily drops as the vapor pressure deficit (VPD) of the air in the measuring system's cuvette or leaf chamber rises. Utilizing this relationship to calculate the foliage-air temperature differential (T_F-T_A) response of these leaves to leaf-chamber air VPD, as per the basic equations of standard heat and water vapor transport theory, we obtain a leaf chamber "non-water-stressed baseline" which is consistent with leaf-chamber measurements of T_F-T_A vs. air VPD. Free-air T_F-T_A vs. air VPD data, on the other hand, produce a relationship which is similarly consistent with a plant stomatal conductance which is invariant with respect to the air VPD. Hence, we conclude that the very act of stomatal conductance measurement alters a potentially-transpiring plant's evaporative water loss rate in such a way that, for very high air VPD conditions, the directly-measured

C_s value (although correct for the leaf in the cuvette or leaf chamber) may be much reduced from that characteristic of comparable non-chamber-encumbered plants in the free air. We then demonstrate that this instrument-induced reduction in directly-measured C_s values is a unique function of the leaf-chamber IJ index, evaluated with respect to the plant's free-air non-water-stressed baseline. Similar results obtained by others for cotton suggest that this phenomenon may be quite general, and that the C_s vs. air VPD interaction, believed by many to be widely operative throughout the plant kingdom, may not really exist in actual field situations.

Idso, S.B., Allen, S.G. and Kimball, B.A. The perils of porometry. IN: Proc. Intern. Conf. on Measurement of Soil and Plant Water Status, Utah State University, Logan, UT. 6-10 July 1987, Vol. 2:133-138.

Measurements of leaf temperature and air temperature and humidity within the cuvette of two different porometers at three different times of year (in three different years) did not produce the classical non-water-stressed baseline previously determined by the non-contact remote sensing technique of infrared thermometry for water hyacinth plants floating under natural conditions out-of-doors with their roots continuously immersed in water, suggestive of a micro-environmental perturbation induced by the imposition of the porometer cuvette about the plant leaf which causes the encompassed stomates to partially close. Furthermore, when the directly-measured leaf stomatal conductance (C_s) data were plotted against the Idso-Jackson (IJ) index values obtained from the porometer-derived leaf and air temperatures and humidity measurements used in conjunction with the non-chamber-encumbered non-water-stressed baseline, a potentially "universal" C_s vs. IJ index relationship was obtained, which relationship has previously been shown to result from the imposition of macro-environmental influences known to restrict stomatal apertures. The nature of this porometer-induced alteration of leaf stomatal conductance was additionally investigated with plants subjected to varying degrees of water stress and varying enhancements of atmospheric CO_2 concentration. In both instances, the micro-environmental perturbation caused by the porometer cuvette decreased linearly with increasing macro-environmental-induced stomatal closure to actually sign above a "free-air" IJ index value of about 0.4. Examples of the seriousness of the porometer-induced error are given, along with procedures for eliminating it.

CO_2 AND PLANTS

Idso, S.B., Kimball, B.A. and Mauney, J.R. Atmospheric carbon dioxide enrichment effects on cotton midday foliage temperature: Implications for plant water use and crop yield. Agron. J. 79:667-672.

In an experiment designed to determine the likely consequences of the steadily rising carbon dioxide (CO_2) concentration of Earth's atmosphere for the foliage temperature, water use, and yield of cotton (Gossypium *hirsutum* L. var. Deltapine-61) plants, cotton was grown out-of-doors at Phoenix, AZ, in open-top, clear-polyethylene-wall, CO_2-enrichment chambers for three summers under mean daylight CO_2 concentrations of 340, 500 and 640 µmol CO_2^{-1} air on an Avondale clay loam soil [fine-loamy, mixed (calcareous), hyperthermic Anthropic Torrifluvent]. Infrared thermometer measurements of the cotton foliage temperature (T_F) indicated that a 330 to 660 µmol$^{-}{}_{1}$ air doubling of the atmospheric CO_2 content results in a midday T_F increase of 1.0°C for well-watered cotton at Phoenix in the summer. This temperature increase was predicted to produce a 9% reduction in per-unit-leaf-area plant transpiration rate and an 84% increase in crop biomass production, which compared favorably with the measured crop biomass increase of 82% for such a doubling of the air's CO_2 content. These findings, together with similar findings for a second plant species -- water hyacinth [*Eichhornia crassipes* (Mart.) Solms] -- allowed us to develop a technique for assessing the effects of a 330 µmol CO_2 mol^{-1} air CO_2 concentration increase on the percentage yield increase (Y) of a crop via infrared thermometry by means of the equation $Y = 7.6\% \times (IJ)^{-1}$, where IJ represents the Idso-Jackson plant water stress index. If this equation holds up under further scrutiny, it could provide a rapid and efficient means for assessing the yield response of crops to atmospheric CO_2 enrichment.

Idso, S.B., Kimball, B.A., Anderson, M.G. and Mauney, J.R. Effects of atmospheric CO_2 enrichment on plant growth: The interactive role of air temperature. Agric. For. Meteorol. 20:1-10.

Comprehensive reviews of the plant science literature indicate that a 300 part per million (ppm) increase in atmospheric carbon dioxide (CO_2) concentration generally increases plant growth by approximately 30%. Working with two species of floating aquatic plants and three terrestrial species, we demonstrate that this stimulatory effect of atmospheric CO_2 enrichment is strongly temperature dependent. Indeed, our results suggest that for a 3°C increase in mean surface air temperature (as is generally predicted to result from the 'greenhouse effect' of such an increase in the CO_2 content of the air), the growth enhancement factor for such a CO_2 increase rises from 1.30 to 1.56. If the non-CO_2 trace gas greenhouse effect is equally as strong, as recent model studies suggest, the growth enhancement factor rises still higher to a value of 1.85. On the other hand, our results also indicate that atmospheric CO_2 enrichment tends to reduce plant growth at relatively cold air temperatures, i.e., below a daily mean air temperature of approximately 18.5°C. As a result, predicting the ultimate consequences of a doubling of the Earth's atmospheric CO_2 concentration may prove to be much more complex than originally anticipated.

Idso, S.B., Kimball, B.A. and Mauney, J.R. Atmospheric CO_2 enrichment and plant dry matter content. Agric. For. Meteorol. (in press)

Fresh and dry plant weights were measured throughout a number of different CO_2 enrichment experiments with six terrestrial plants and two aquatic species. Similar data were also extracted from the literature for 18 additional plants. In general, CO_2 enrichment had little effect on plant percent dry matter content, except under conditions conducive to starch accumulation in leaves, and then it caused an increase in percent dry matter content.

Idso, S.B. The three phases of plant response to atmospheric CO_2 enrichment. Plant Physiol. (in press)

Several years of research on seven different plants (five terrestrial and two aquatic species) suggest that the beneficial effects of atmospheric CO_2 enrichment may be divided into three distinct growth response phases. First is a well-watered optimum-growth-rate phase where a 300 ppm increase in the CO_2 content of the air generally increases plant productivity by approximately 30%. Next comes a non-lethal water-stressed phase where the same increase in atmospheric CO_2 is more than half again as effective in increasing plant productivity. Finally, there is a water-stressed phase normally indicative of impending death, where atmospheric CO_2 enrichment may actually prevent plants from succumbing to the rigors of the environment and enable them to maintain essential life processes, as life ebbs from corresponding ambient-treatment plants.

Idso, S.B. Comments on "Biotic changes consistent with increased seasonal amplitude of atmospheric CO_2 concentrations" by R.A. Houghton. J. Geophys. Res. (in press)

In his analysis of possible biotic explanations for the observed increase in the seasonal amplitude of the Earth's atmospheric CO_2 concentration over the period 1958 to 1982, Houghton [1987] concludes that the changes in plant metabolism required to produce the measured increase in CO_2-cycle amplitude are "too large to be explained by CO_2 fertilization," in that they require "a biotic growth factor 2 to 4 times higher than most short-term experimental evidence suggests." I show herein, however, that there are several well-documented phenomena which could significantly increase the basic growth response of plants to atmospheric CO_2 enrichment by an amount which would make this mechanism fully capable of producing the changes in Earth's CO_2-cycle amplitude measured over the past quarter-century, noting further that it has also been admitted by others who have studied this problem that no alternative phenomenon yet suggested even comes close to providing a likely explanation for what has been observed.

Idso, S.B. Detection of global carbon dioxide effects. Nature 329:293.

After reviewing a number of recent pertinent studies, it is concluded that the case for global CO_2 effects on worldwide vegetative productivity appears to be firm. We know, for instance, that the terrestrial biota is responsible for the seasonal cycle itself and that amplification of the cycle with time appears to be explicable only in terms of CO_2-induced stimulation of photosynthetic activity. Now, it also appears that a unique asymmetry in the interannual variation in the seasonal cycle is also explicable only in terms of photosynthetic variations. Hence, we appear to have little recourse but to acknowledge the reality of this ubiquitous phenomenon, as many have already done. Indeed, as Morison (Nature 327.566;1987) has recently noted with respect to a number of these studies, they emphasize "that the global rise in CO_2 is already having important effects on the biosphere."

CO_2 AND CLIMATE

Idso, S.B. Greenhouse warming or Little Ice Age demise: A critical problem for climatology. Theoret. Appl. Climatol. (in press)

A comparative analysis of long-term (several-hundred-year) temperature and carbon dioxide (CO_2) trends suggests that the global warming of the past century is not due to the widely accepted CO_2 greenhouse effect but rather to the natural recovery of the Earth from the global chill of the Little Ice Age, which was both initiated and ended by some unrelated phenomenon, the latter expression of which is the very warming generally attributed to the CO_2 increase of the past century. As a result, gaining a better understanding of the Little Ice Age looms as a critical problem in the climatology of the past with important implications for the climatology of the future.

Idso, S.B. CO_2 and sea level. J. Coastal Res. 3(4):ii–iii.

The last several years have witnessed a major effort by a dedicated group of highly visible and influential scientists to convince the governments of the world that mankind faces a serious threat of significant sea level rise as a result of the steadily increasing carbon dioxide (CO_2) concentration of Earth's atmosphere. This warming, together with an equivalent warming which is predicted to result from concurrent increases in other radiatively-active trace gases, could create severe problems for coastal areas, if sea level rises in response to the melting of large volumes of polar ice. However, there is no rational basis for believing these doomsday predictions. Hence, although we should always be wary of potential threats to the global environment, there would seem to be little reason to worry about the rising CO_2 content of Earth's atmosphere. In fact, there is overwhelming direct experimental evidence that this phenomenon will greatly increase the biological productivity of the globe; and there is almost irrefutable evidence that the biosphere is already responding globally to the CO_2 increase of the past century and may be a blessing in disguise.

Idso, S.B. The CO_2/trace gas greenhouse effect: Theory versus reality. Theor. Appl. Climatol. 38:55-56.

The CO_2/trace gas greenhouse effect theory predicts that between 1880 and 1980 the northern third of the Earth should have warmed by about 5.7K. However, the actual observed warming of this region over this time period is seen to be only about 0.5K, or less than a tenth of what is predicted. In view of these facts, I find it hard to believe that the current CO_2/trace gas greenhouse effect theory is not grossly in error. Do we not thus have a moral responsibility to acknowledge that likelihood? I believe that we do, and that we also have a professional obligation to strive to resolve the dilemma it presents.

Idso, S.B. Me and the modelers: Perhaps not so different after all. Climatic Change. (in press)

Throughout the course of the CO_2/climate controversy of the past decade, I have invariably found myself at odds with most of the climate modeling community. Many times, however, these differences have been more a matter of interpretation and emphasis than they have of substance. Hence, I feel an obligation to publically state that when it comes to our separate assessments of the state-of-the-art of climate modeling, we appear to be in near perfect agreement. My basis for this statement comes from the recent review article of Schlesinger and Mitchell (Rev. Geophys. 25:760-798), and its somewhat longer forerunner published by the U.S. Department of Energy in 1985. After studying their careful analyses in some detail, I can truthfully say that I concur in every single word of their conclusions and suggested goals of future research. And judging from the list of people they acknowledge as having reviewed both versions of their paper, I would seem to be in good climate modeling company in this concurrence.

Idso, S.B. The atmospheric effects of nuclear winter — a review. Atmos. Environ. (in press)

Are volcanic explosions valid analogues of nuclear detonations with respect to the effects which both phenomena may have on Earth's climate? This important question has recently been the focus of some discussion. In this additional contribution to that debate, I review the topic in some detail within the context of the "nuclear winter" hypothesis, finding that proponents of that theory relied on a very tenuous volcano/climate relationship to lend credence to their model predictions of post-war climatic catastrophe.

WHEAT

Reginato, R.J., Hatfield, J.L., Bauer, A., Hubbard, K.G., Blad, B.L., Kanemasu, E.T., Major, D.J. and Verma, S.B. Winter wheat response to water and nitrogen in the North American Great Plains. Agric. For. Meteorol. (in press)

A unique, identical experiment was conducted at five locations in the North American Great Plains, from Alberta, Canada to Texas, USA, in 1985 and 1986, to investigate the response of winter wheat (*Triticum aestivum* L.) to water and nitrogen fertility treatments under these climatic regimes. The experimental design consisted of four nitrogen levels, three irrigation regimes, two cultivars, with four replications. One cultivar, Colt, was common to all locations. Crop response throughout the growing season was monitored by intensive plant sampling, measuring spectral reflectance, evaluating canopy temperature, and by detailed measurements of the microclimate and of soil water content. This paper discusses the procedures common to all locations. The papers which follow in this issue present the results and significance of these experiments, each paper treating a different aspect of the experiment across locations.

Zipoli, G., Pinter, P.J., Jr., Reginato, R.J., Jackson, R.D. and Idso, S.B. Canopy temperatures for assessing water use and yield performance of wheat cultivars. IN: Proc. Intern. Conf. on Measurement of Soil and Plant Water Status, Logan, UT. 6-10 July 1987. Vol. 2:93-98.

Six cultivars of spring wheat (*Triticum aestivum*, L.) representing lines which had been selected for relatively high yield potential under water limiting conditions were grown under well-watered and drought-stressed irrigation regimes in Phoenix, AZ. Midday canopy temperatures were measured daily using handheld infrared thermometers. Water use was estimated by soil water depletion information obtained with neutron scattering techniques three times a week. Yield components were determined at harvest. Cultivars with the highest average canopy temperatures under well-watered conditions used the least amount of water and performed the best when exposed to drought stress during development. Those exhibiting the coolest midday temperatures used a maximum amount of water and yielded poorly when compared with a non-stressed check. Results suggest that canopy temperatures may be a useful non-destructive technique for determining relative yield performance of cultivars subjected to water shortage during growth.

NEUTRON PROBE

Reginato, R.J. and Nakayama, F.S. Neutron probe calibration based on plastic transfer standards. Soil Science. (in press)

An accurate calibration of a neutron probe for the field measurement of soil water content is not a simple task. The most straightforward calibration technique is done in the field by determining the volumetric soil water content of soil cores taken around the access tube and relating it to the instrument reading. Although the sampling procedure is time consuming and sometime arduous, it is probably the most accurate method currently in use. Plastic cylinders of different outside diameters have been found to be valuable intermediate standards for transferring the field calibration from one neutron probe to another when the detector type, source strength and geometry are similar. This new technique will greatly facilitate the calibration of any number of neutron probes in many different soils.

COMPARISON OF BLACK BODY CALIBRATION DEVICES

Portable black body calibration devices (BB) incorporating a thermistor sensor imbedded in a circular metal "bullseye" and a LCD readout of target temperature are commonly used to check the performance of handheld infrared thermometers (IRT) during agricultural field experiments. The amount of time required for these passive instruments to achieve thermal equilibrium with ambient temperature conditions and confirmation that IRT's can be compared with the BB readout display even during conditions of rapidly changing temperatures was investigated in a prior report. Since that time a number of these devices have been acquired from Everest Interscience Inc. Because these BB's are often used interchangeably between experiments and some investigators derive an IRT correction factor from checks made before and after each field experiment, we deemed it appropriate to investigate their behavior in more depth.

Accordingly, a laboratory evaluation was performed to address several concerns expressed by individuals using the BB's. First, we examined how closely the BB's corresponded with an independent measure of air temperature measured with a mercury-in-glass, NBS traceable thermometer. Second, we observed the amount of time required for BB's enclosed in an insulated, protective housing to come to thermal equilibrium with ambient temperature. Finally, we investigated the relationship between surface and the display temperature of the BB under changing conditions approximating those encountered when the device encounters a large step change in ambient temperature.

Methodology and results

The first experiment was designed to compare the factory-set thermistor calibration of the BB's with ambient air temperature and also with the surface temperature of the BB's as measured with an IRT. Five BB devices were removed from the insulated boxes which are normally used in our field experiments and placed adjacent to one another in a constant temperature room wherein the ambient temperature could be controlled to approximately ± 1.0°C. Then approximately 2 hours after the room had stabilized at a temperature of about 10°C, the LCD display of each BB was recorded along with the air temperature measured with an NBS traceable thermometer which could be read to the nearest 0.1°C. The surface temperature of each BB was also measured with an Everest Interscience IRT

(SN 138; 15° field-of-view; 8-14 μm bandpass filter). The room temperature was then increased by several degrees, allowed to stabilize for about an hour and new readings were recorded. This procedure was repeated at temperatures representative of those which might be encountered in our field experiments.

Results showing correspondence between the BB display and air temperature of the room are given in Table 1. Discrepancies of -1.1 ± 0.2°C were noted at the 3 coldest temperatures. These were probably due to the fact that the room was gradually warming and the BB's were not in thermal equilibrium with the ambient room temperature. At room temperatures of 18.7°C and above, correspondence between the display and room temperature were excellent.

We also found good agreement among the BB's at all room temperatures. The individual deviations of each BB from the average temperature sensed by all the BB's are shown in Figure 1. Overall, these deviations were relatively small, on the order of 0.1 to 0.2°C. For the majority of agricultural research purposes, errors of this magnitude can probably be ignored, considering the ± 1°C stated accuracy of most handheld IRT's. This implies these devices could be used interchangeably between experiments without introducing substantial bias into the data.

The BB display was consistently about 0.5°C warmer than the temperature measured with IRT SN 138 (Table 2). These deviations may be due to the calibration of the IRT since an independent check using an Advanced Kinetics extended blackbody also indicated a similar tendency at some ambient temperatures. If this offset is taken into consideration, the BB display and IRT show excellent agreement over the entire range of ambient temperatures between 9.7 and 38.1°C.

The second phase of our investigation examined the time constant of the BB's when exposed to a step change in ambient temperature. This was designed to simulate conditions that might be encountered when a BB was taken from a building or automobile into the field where temperatures might be considerably warmer or cooler. BB's were first equilibrated to room temperatures of about 25-27°C, then they were transferred to a constant temperature room where the temperature was controlled (± °C) to simulate either warm (39°C) or relatively cool (15°C) conditions. In this experiment, all of the BB's were enclosed in the insulated boxes that we usually use in field experiments. Every 10 minutes, the doors of the boxes were opened, display temperatures noted and the doors quickly shut again. Ambient room temperatures were recorded via the mercury-in-glass, NBS traceable thermometer.

Results for 5 of the Everest BB's are shown in Figures 2 and 3, along with the trend in ambient room temperature. As expected the BB's required a long time to approach thermal equilibrium. In fact after 3 hours of monitoring, we terminated the experiment even though the displayed temperature still had not reached the room temperature. If we define the time constant as the time required for a device to achieve a 65% response to a step change in ambient conditions, we find that it took about 90 min. for the warmer room temperature and about 100 min. for the cool room. The time constant for 90% response was 125 min. and 170 min. for the warm and cool rooms, respectively. These data are about twice as long as those shown in the 1981 Annual Report for BB's without insulated boxes (Figure 1; p. 188). We noticed that one BB (SN 100) had a time constant that was shorter than the others. After the first 20-30 min. of the experiment it was consistently about 1°C below (cool room) the other BB's. Closer inspection revealed that the circular black aluminum target on BB SN 100 was 6mm thick while that of the others was 15.5mm in thickness. The smaller mass required less time to respond to changing ambient conditions. This BB was also evaluated in the 1981 study and was found to have a shorter time constant.

Figure 4 shows results of a similar test conducted with two of the BB's evaluated earlier and two additional BB's that are used at the laboratory. One set of BB's (SN 102 and 7418) were tested in the insulated boxes as before; the second set (SN 103 and 130) were tested without the boxes, just as they are sold by the manufacturer. These conditions are labeled "BB W/BOX" and "BB W/O BOX" in the figures. The difference in time constants between the two conditions was dramatic. The BB's in insulated boxes reached 65% response within 100 minutes but it only took 20 minutes to achieve the same response without the box. After 1 hr. the unboxed BB's reached 90% of the total response.

An IRT SN 138 was used to measure the radiometric surface temperatures of the above BB's during the same test. Results show very good agreement between the display temperature and that estimated using the IRT (Figure 5). This indicates that the IRT can be checked with the BB calibration device in the field under non-equilibrium temperature conditions.

Conclusions

Laboratory testing of 7 portable Everest black body calibration devices (BB) revealed performance characteristics acceptable for general field use. Temperatures displayed by the devices corresponded well with air temperatures measured with a reference mercury-in-glass thermometer. In addition, we found that all BB devices agreed closely with one another despite the fact that several had been in continuous use for 6-8 years. The time required for the BB's to come into equilibrium with a new ambient temperature depended on the insulating properties of the protective housing. An unshielded BB reached 65% of its total response in about 20 min. while a BB housed in the insulated boxes we commonly use in our field experiments required 90-100 min. to achieve the same response. This long response time however, does not affect the BB use in the field. We found good agreement between surface temperature of the BB target and the BB display even under changing ambient temperature conditions.

LYSIMETER FIELD

During 1987, a subsurface trickle irrigation system was installed in the lysimeter field. From the main water line used for flood irrigation, another line was connected for the trickle system. A valve, sock-type filter, and pressure regulator were connected in series before the main distribution line. Submains went to each plot through a solenoid valve (on-off), two manual readout water meters (metric), a venturi unit for adding liquid fertilizer, and an air relief valve. The controls for each of the subplots (A,B,C) were placed on the north side of the upper berm for each of the main plots (1-6). Flush lines were installed with valves in order to be able to clean out the lines as needed.

The lysimeters were not plumbed separately, but were connected into the regular field lines by going over the rim of each lysimeter. This posed a few problems (the proper number of emitters in the one square meter, etc.), but by trial and error and the installation of valves, the problems are now minimal.

The double tube trickle lines, with emitters spaced at 30 cm intervals, were buried 22 cm deep and were spaced 50 cm apart. This arrangement is more than double the capacity of conventional systems, but we designed ours such that we should be able to keep plants well watered and maintain the soil surface either dry or wet. Also, we wanted to be able to put on a significant amount of water in as short a time as possible. For plots 1, 2, and 3 the lines were buried in an east-west orientation, and for plots 4, 5, and 6, the lines ran north-south. This gave us the opportunity to study the effects of row orientation on our remotely sensed data.

All the supplies were purchased from a single company, and the system was installed with local slave labor, who did an outstanding job. It has taken several months to work out the bugs and to learn how to use the system. Until the new data logger and control system is received and installed, we still have to turn the solenoid on and off by hand in order to irrigate each plot.

MACII

Introduction

An experiment was conducted during the second week of June 1987 at the University of Arizona Maricopa Agricultural Center, 40 km south of Phoenix, AZ. The purpose of this study was (1) to assess the spatial and temporal distribution of evapotranspiration, ET, over several agricultural fields, (2) to assess the potential of using bare soil surfaces of different roughnesses (low reflectances) to evaluate atmospheric models for interpreting aircraft and satellite data, and (3) to investigate the possibility of calculating aerodynamic resistance over partial canopy cover. A unique part of this experiment was that the 27 participants, representing 7 departments from 5 universities, 6 offices from 3 federal agencies, 2 private institutions and 1 foreign national agency, were funded by their respective organizations for their part in the overall experiment. This report includes individual contributions from several of the participants, each composing a single chapter. What follows is a brief description of the experiment.

A Landsat overpass occurred on 11 June 87 and SPOT on 09, 13 and 14 June. Weather conditions for the SPOT were excellent, but the 11th was cloudy, so no TM data were obtained. Low level (150 m) aircraft spectral data were collected on the 09th, 11th and 14th of June. Mounted in the airplane were a four-band radiometer with (as appropriate) TM or SPOT filters, an infrared thermometer, a video camera (to see the areas flown over) and a data logger collecting the data over all areas of interest. The fields of view of the various instruments and the speed and altitude of the aircraft resulted in about 18 to 20 observations (40 m diameter circles) being taken over a 1.6 km path. There were 10 such paths (different surfaces) over which the aircraft flew.

Ground-based instruments were used to evaluate atmospheric, soil and plant properties at various times during the week-long experiment. The optical depth of the atmosphere was determined in order to allow a comparison between satellite-, aircraft-, and ground-based reflectance factors. Untethered radiosonde data were also collected to aid in characterizing the atmosphere. Reflectance data were collected over bare soil, disked wheat stubble, alfalfa and cotton for comparison with aircraft and satellite data. Over a moderately rough soil an 8-band multi-modular radiometer with TM filters and a 4-band radiometer similar to that mounted in the aircraft were hand carried in a nadir position over a series of transects covering a 16 x 4 TM pixel area. Another identical 4-band radiometer with SPOT filters was used to collect data over alfalfa, cotton, bare soil, and recently plowed wheat stubble. The radiometer was held at the same look angle as the SPOT satellite in addition to a nadir view. These data were collected at the same time of the satellite overpass, which coincided with the aircraft overflight.

Additional ground-based measurements were designed to examine the effect of sensor viewing angles on the apparent reflectance factors of 7 representative ground cover classes present at MAC on both days of the overpass. This experiment utilized a handheld Exotech radiometer equipped with filters similar to those on the SPOT platform to obtain data along transects in cotton with east-west row orientation, well-watered and stressed alfalfa fields, disked wheat stubble, laser leveled soil fields, rough soil fields and the farm access roads. Results demonstrated the efficacy of a handheld radiometer in gathering ground truth reflectance data. For most of these cover classes this was the only source of information concerning the directional reflectance properties during the time of each satellite overpass. Results illustrated the dependence of bidirectional reflectance properties on wavelength interval and physical characteristics of the target. For the soil targets, micro-topography of the surface and the shadowing associated with it produced had the largest influence on bidirectional reflectance properties. Smoother surfaces displayed much less variation with changing radiometer viewing direction. In non-vegetated targets, off-nadir reflectances in each wavelength were affected similarly. However, visible and near-IR wavelengths behaved quite differently when vegetated targets were viewed from an off-nadir direction. This was attributed to the relative high transparency of plant leaves to near-IR light. It was especially pronounced because of the partial alfalfa and cotton cover. But the same effect is expected to persist for denser canopy cover conditions. The handheld data also documented several cases where the actual ground reflectances changed from one day to the next. In one instance it was because the surface soils were drying after an irrigation; in another the alfalfa plants were actually growing so rapidly that more biomass was changing in the 24h period. The point was made that these changes were real and reflectance differences from one day to the next in the satellite data cannot be attributed solely to differences in view angle and atmospheric conditions.

Plant and soil temperatures, both shaded and unshaded, were taken half-hourly from about 0800 to 1300 each day with hand-held infrared thermometers in a cotton field which had about 20-25% canopy cover. This information was collected to examine how one might be able to extract plant temperature from a composite temperature measured from the aircraft or satellite. Additionally, these data were to be used in the calculation of aerodynamic resistance where the surface temperature is a primary factor. Adjacent to one of the two surface temperature measurement sites was a tower upon which air temperature and windspeed profiles were measured. Plant, soil and air temperatures and windspeed measurements were taken to examine the calculation of aerodynamic resistance over a regular, but partial, canopy cover.

Measurements of latent heat flux on the ground were obtained from 4 Bowen ratio systems and 4 eddy correlation systems based over cotton, alfalfa and bare soil. These systems operated almost continuously for the 5-day period. A balloon tethered over alfalfa was used to measure profiles of air temperature, dew point and windspeed to a height of 100 m to examine the development of the boundary layer and to assess the contribution of advected energy to the latent heat flux. In addition to these detailed micrometeorological measurements, half-hourly values of routine weather data were collected around the farm from 3 weather stations.

To characterize the cotton field, various plant measurements were made. Canopy cover was determined photographically and from measurements of plant height and width. From plant samples taken to the laboratory, leaf area and biomass were determined. Also, leaf angle measurements were made on cotton plants from about 0900 to 1500 h for 3 days. Stomatal conductance of cotton was measured diurnally for 5 days with a commercial diffusion porometer.

The twenty-seven people who actively participated in this week-long experiment represent the following institutions:

U.S. Department of Agriculture, Agricultural Research Service
Water Conservation Laboratory, Phoenix, AZ
Hydrology Laboratory, Beltsville, MD
Remote Sensing Laboratory, Beltsville, MD

U.S. Department of Interior, Geological Survey
Water Resources Division, Phoenix, AZ
Water Resources Division, San Diego, CA

University of Arizona
Agricultural Engineering Department, Tucson, AZ
Optical Sciences Center, Tucson, AZ
Natural and Renewable Resources Department, Tucson, AZ
Soil and Water Science Department, Tucson, AZ

Utah State University
Soil Science and Biometeorology Department, Logan, UT

National Aeronautics and Space Administration
Laboratory for Terrestrial Physics, Greenbelt, MD

New Mexico State University
Agriculture Department, Las Cruces, NM

Ministry of Agriculture, Forestry and Fisheries
National Agriculture Research Center, Yatabe, Tsukuba, JAPAN

Kansas State University
Evapotranspiration Laboratory, Manhattan, KS

ERDA, Inc., Atlanta, GA

Battelle Pacific Northwest Laboratories
Terrestrial Sciences Section

SOIL AND PLANT EMISSIVITY

Introduction

The use of infrared thermometry (IRT) to measure surface temperature is becoming more common with the availability of small, easy-to-use IRT's. These units can measure absolute temperatures for a blackbody surface with an emissivity of unity. However, surfaces encountered in the field have emissivity values less than one, and we cannot accurately calculate the surface temperature without knowledge of an object's emissivity.

Emissivity is defined as the ratio of the emittance of a given surface at a specified wavelength and temperature to the emittance of an ideal blackbody at the same wavelength and temperature. Several procedures have been proposed for the calculation of the emissivity of different surfaces. The purpose of this study was to evaluate the emissivities of soils and plants at the University of Arizona Maricopa Agricultural Center (MAC) for use in experiments to assess evapotranspiration using remotely sensed parameters.

Methods and materials

The equipment used to determine emissivities was an Everest infrared thermometer with a 15 degree field-of-view and a 8-14 μm bandpass inserted into a 63 centimeter-tall "skewed" aluminum cone similar to the one described by Fuchs and Tanner (1966). Measurements were made before dawn under clear sky conditions. Emissivity was calculated from the data according to the expression

$$\varepsilon_\lambda = (T_\lambda^4 - T_b^4)/(T_s^4 - T_b^4) \qquad (1)$$

Where ε_λ is the thermal emissivity for the spectral band used in temperature determinations, T_λ is the brightness temperature (in degrees Kelvin) of the exposed surface measured by the radiometer, T_b is the radiation temperature of the global background environment (sky brightness temperature), and T_s is the measured radiation temperature of the surface when covered by the low emissivity cone (assumed to be the thermodynamic temperature).

The infrared thermometer (IRT), connected to a data logger, was inserted into the cone, and the first measurement consisted of obtaining the sky temperature (T_b). This was done by pointing the IRT skyward up 45 degrees from the horizon, and taking 10-12 measurements in that many seconds as the IRT was rotated in a circle at that orientation. These measurements were taken before and after the surface readings. The total 20-24 "circle" readings were averaged to obtain a single value for use in Eq. 1. Previous observations of sky temperature indicated that this was a rather simple method and agreed quite well with another procedure which averaged a dozen readings taken in each of two transects (north-south and east-west) traversing arcs of about 160 degrees from about 10 degrees above the horizon in the north (east) to the south (west). Next the IRT was pointed towards a soil or plant about 1-2 meters distant, and 6 readings were taken (T_λ). Then the cone and IRT were placed very rapidly over that observed area, and after completely covering the surface, the first surface temperature (T_s) reading was recorded.

Results

The three temperature measurements were then used in Eq. 1 to determine the emissivity of bare soil with varying surface roughness and of cotton. There were five surfaces in common for 1986 and 1987, and the calculated emissivities and standard deviations are given below:

Emissivity

Surface	1986	1987
Dry bare soil, medium rough	0.962 + 0.005	0.965 + 0.021
Dry bare soil, rough	0.967 + 0.006	0.961 + 0.012
Dry soil with plowed straw	0.969 + 0.007	0.973 + 0.018
Cotton plants 30 cm tall	0.987 + 0.006	0.978 + 0.010
Dry soil in cotton furrow	0.984 + 0.002	0.982 + 0.008

These data demonstrate that bare soils, regardless of the surface condition normally encountered in the field, have an emissivity of 0.96, but the soil that was plowed and has some straw exposed has a slightly higher emissivity, 0.97. The cotton plants and the soil in the furrows under the cotton have an emissivity of about 0.985. It is of interest to note that the calculated emissivities for both years are quite similar.

PERSONNEL

R. J. Reginato, R. D. Jackson, S. B. Idso, P. J. Pinter, Jr., M. S. Moran, T. R. Clarke, R. S. Seay, S. M. Johnson, C. E. McGuire, B. L. Carney, B. L. Murphy.

Table 1. Differences (°C) between room temperature (measured with the NBS traceable thermometer) and the LCD display temperature of each Everest Interscience blackbody calibration device. Positive values indicate that the BB device measured a temperature warmer than the room temperature.

Room Temp. (°C)	BB DISPLAY MINUS ROOM TEMPERATURE (°C)				
	SN 45	SN 88	SN 100	SN 102	SN 103
9.7	-0.9	-1.0	-1.0	-1.0	-1.0
10.5	-1.1	-1.2	-1.1	-1.4	-1.5
12.8	-0.8	-1.1	-1.2	-1.3	-0.8
18.7	-0.1	-0.2	-0.3	-0.3	-0.2
19.0	-0.2	-0.3	-0.3	-0.4	-0.3
20.4	-0.3	0.0	-0.4	-0.1	+0.1
20.4	+0.1	+0.2	+0.2	+0.2	+0.3
26.5	+0.1	+0.1	0.0	0.0	0.0
26.6	+0.2	+0.1	+0.1	0.0	+0.1
30.2	-0.3	-0.2	-0.1	0.0	0.0
30.7	0.0	0.0	+0.1	+0.1	+0.1
33.7	+0.3	+0.4	+0.5	+0.4	+0.4
33.7	+0.3	+0.4	+0.6	+0.5	+0.4
38.4	+0.3	+0.4	+0.5	+0.5	+0.4
38.1	+0.4	+0.6	+0.7	+0.7	+0.6
Mean	-0.13	-0.12	-0.11	-0.14	-0.09
SD	0.47	0.57	0.61	0.64	0.59

Table 2. Differences between the BB displays and the radiant surface temperature measured with an IRT (SN 138). Positive values indicate the BB was warmer than the IRT measured temperature.

ROOM TEMP. (°C)	BB DISPLAY MINUS IRT TEMPERATURE (°C)				
	SN 45	SN 88	SN 100	SN 102	SN 103
9.7	0.3	0.3	0.1	0.1	0.2
10.5	0.1	0.3	0.0	0.0	0.2
12.8	0.3	0.3	0.3	0.1	0.2
18.7	0.5	0.5	0.4	0.4	0.5
19.0	0.5	0.4	0.5	0.4	0.5
20.4	0.5	0.6	0.5	0.5	0.6
20.4	0.5	0.5	0.5	0.5	0.6
26.5	0.5	0.7	0.6	0.7	0.4
26.6	0.6	0.6	0.7	0.6	0.7
30.2	0.6	0.6	0.7	0.7	0.7
30.7	0.6	0.6	0.7	0.7	0.7
33.7	0.5	0.5	0.7	0.7	0.7
33.7	0.5	0.5	0.7	0.7	0.7
38.4	0.4	0.4	0.6	0.7	0.7
38.1	0.4	0.5	0.6	0.6	0.7
Mean	0.45	0.49	0.51	0.49	0.54
SD	0.14	0.12	0.22	0.24	0.20

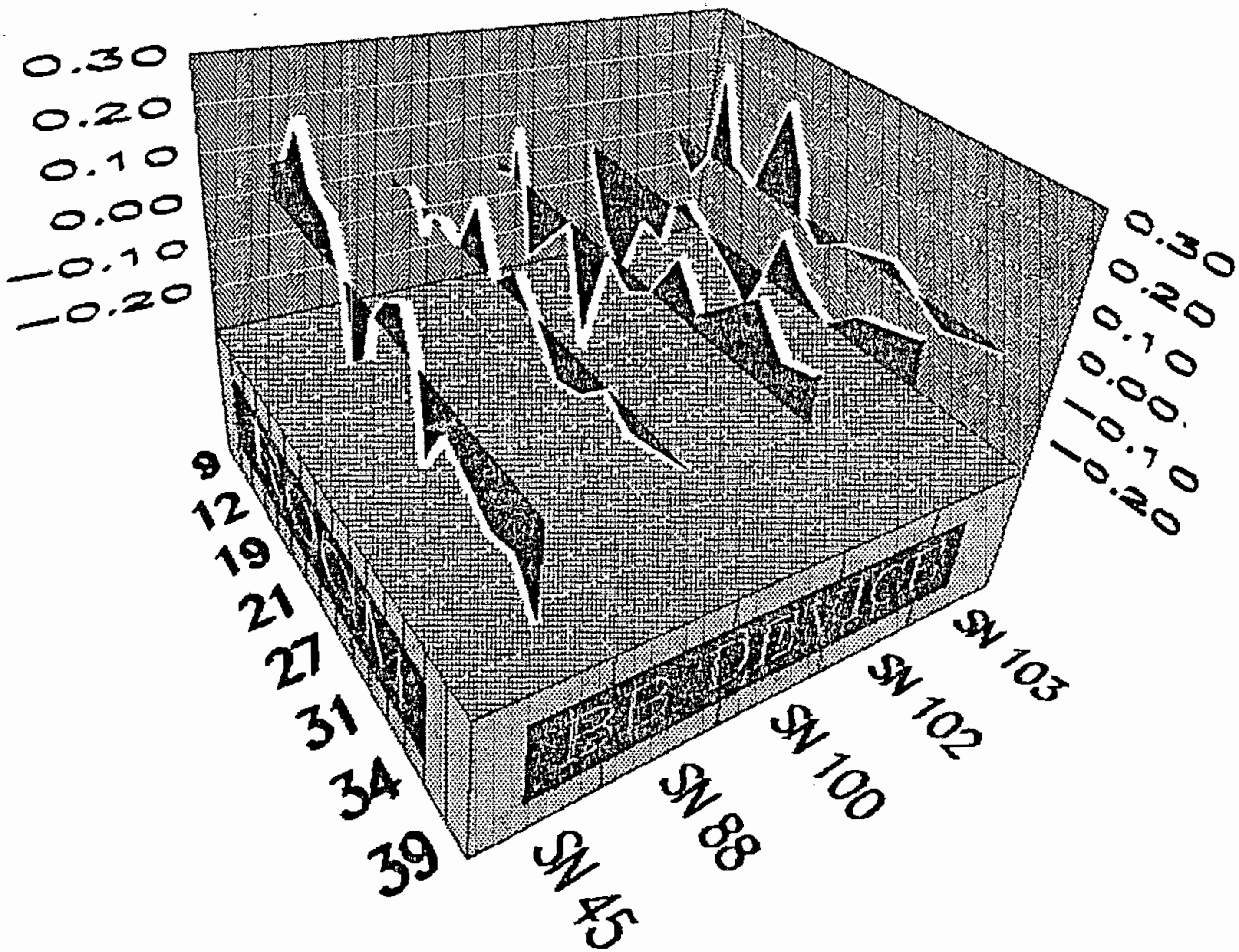

Figure 1. The deviation (in °C) of each BB's display temperature from the average of all five display temperatures at various ambient room temperatures. In this 3-dimension representation, peaks indicate individual BB values higher than average while valleys indicate values lower than average.

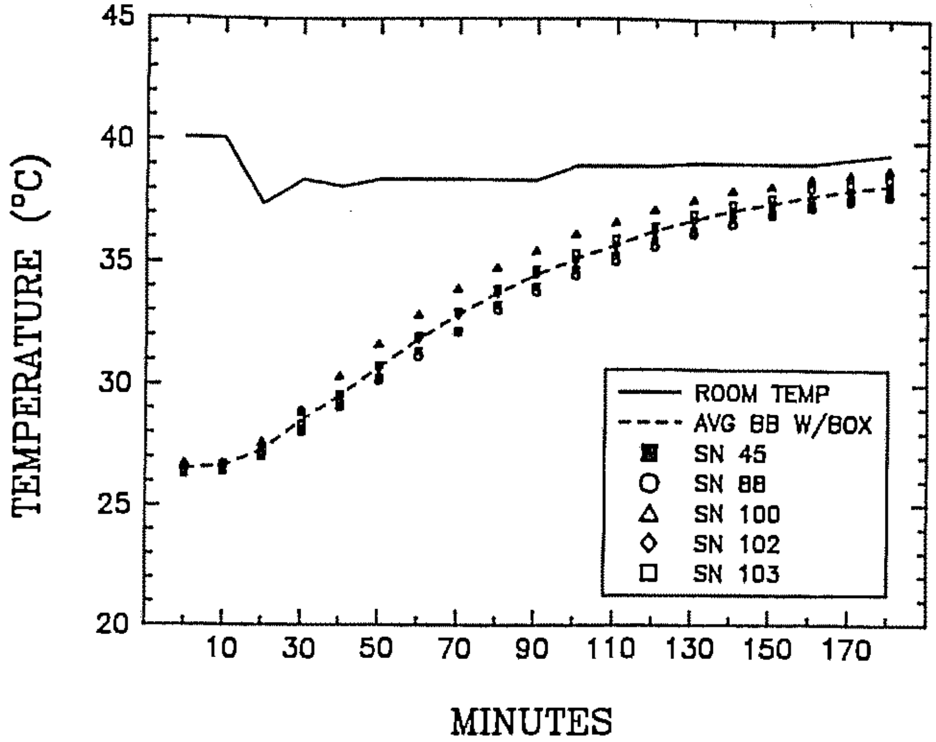

Figure 2. Everest black body response to a step increase in ambient temperature. Data are shown for five BBs in insulated boxes; room temperatures were measured with a NBS traceable thermometer.

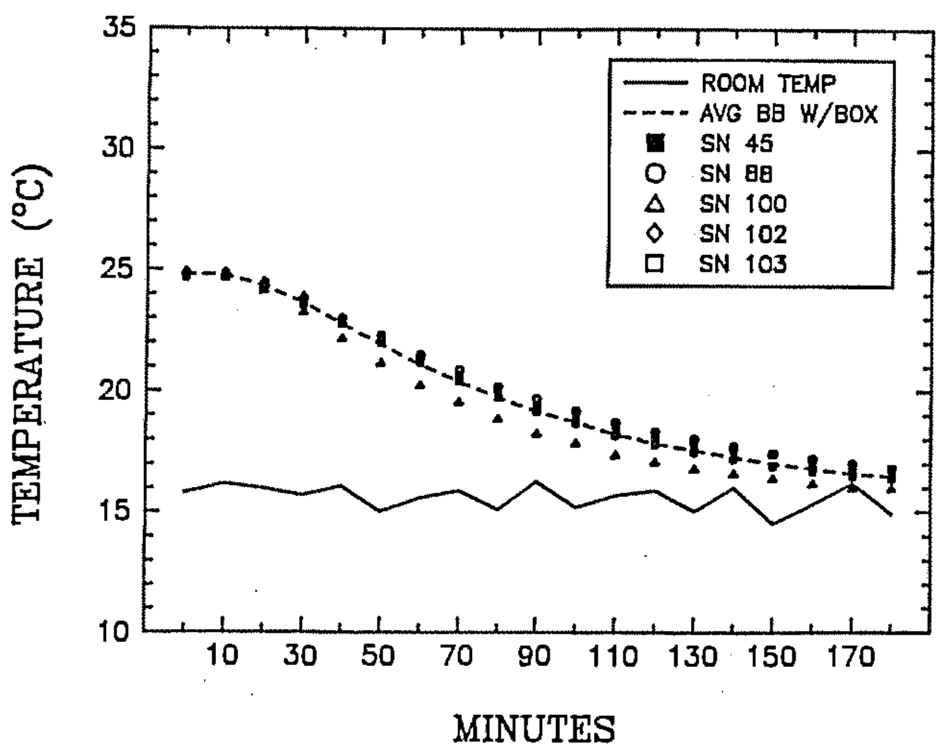

Figure 3. Everest black body response to a step decrease in ambient temperature. Data are shown for five BBs in insulated boxes; room temperatures were measured with a NBS traceable thermometer.

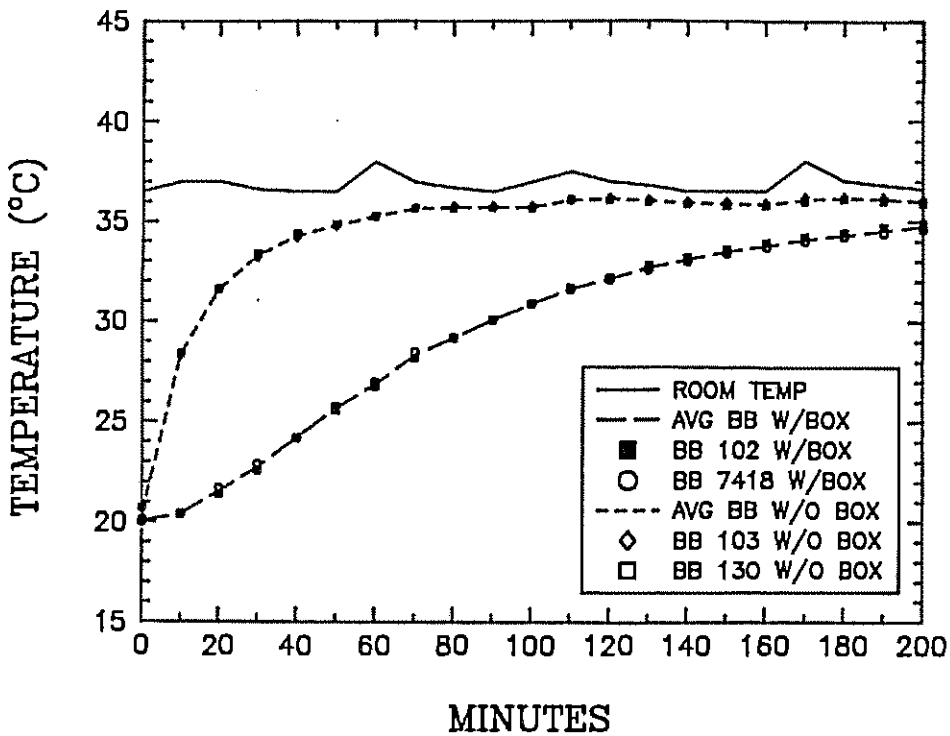

Figure 4. Everest black body response to a step increase in ambient temperature. Average data for two BBs in insulated boxes and two BBs without boxes are shown with room temperatures measured with the NBS traceable thermometer.

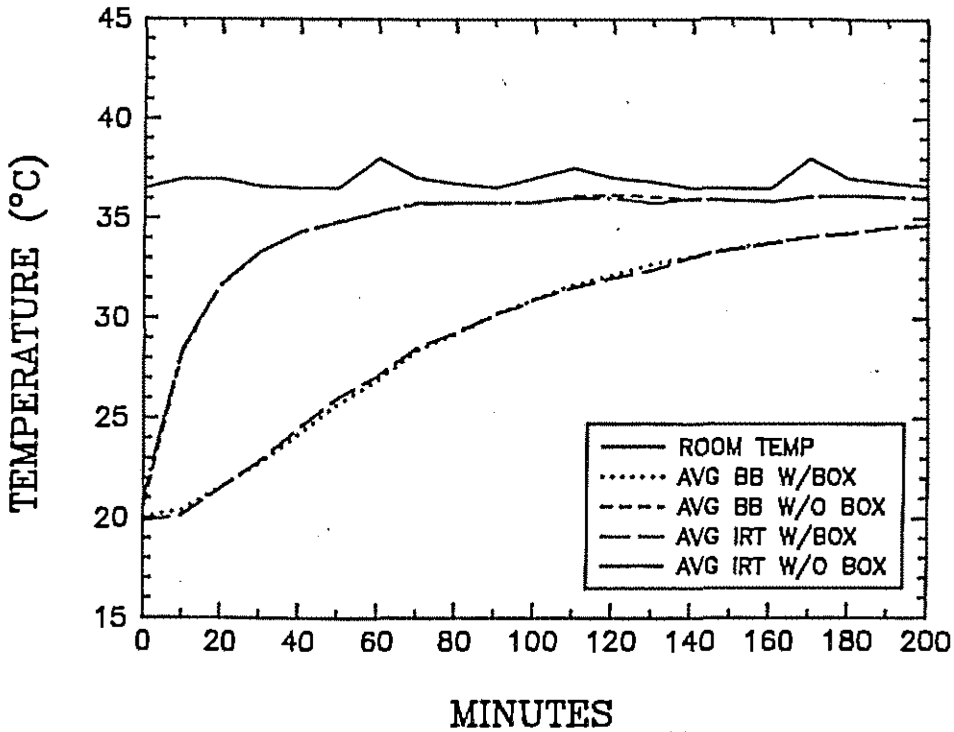

Figure 5. Comparison of IRT surface temperatures with BB display temperatures during a step change in ambient room temperature. Averages for two BBs in insulated boxes and two BBs without boxes are shown with room temperatures measured with the NBS traceable thermometer. A uniform 0.5 °C offset was added to the surface temperatures of the BBs that were measured with IRT SN 138 (15°fov, 8-14μm).

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TITLE: EFFECTS OF INCREASING ATMOSPHERIC CO_2 ON YIELD AND WATER USE OF CROPS

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OUTLINE

INTRODUCTION

To determine the effects of the increasing atmospheric CO_2 concentration on the growth and water use of crops, the U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory cooperatively conducted two experiments during 1987. In the larger experiment, which was being conducted for the second year, the effects of the three-way interaction between increased CO_2 concentration, water stress, and low fertility on the growth of cotton were investigated. Secondary objectives were to determine the effects on the physiological determinants of crop yield, on water stress and stomatal behavior, and on biochemical reactions that limit photosynthesis. Open-top chambers were used to confine the CO_2 around the field-grown cotton.

In many prior experiments reviewed by Kimball (1983) conducted under mostly ideal conditions in greenhouses and growth chambers, and also in field experiments conducted by us (Kimball et al., 1983, 1984, 1985) under well-watered and fertilized conditions, most crops and cotton in particular have produced large increases in yield with a doubling of CO_2 concentration. However, much of the world's agriculture and the unmanaged biosphere suffer often from insufficient water and nutrients. Consequently, a multivariate experiment was needed to determine how productivity will be affected under conditions of water and nutrient stress in the future high CO_2 world. In 1986 we (Kimball et al., 1986) conducted such an experiment, and in 1987 we sought to replicate that experiment in time, which is the first topic of this report.

In the second experiment conducted in 1987, the effects of CO_2 on cotton growing in an open field were observed. The CO_2 was applied using two methods: (1) irrigating with carbonated water (fizz water), and (2) releasing gaseous CO_2 at the soil surface -- a free-air CO_2 enrichment (FACE) experiment. This experiment too was the second year of an experiment initially conducted in 1986 (Kimball et al., 1986). The impetus to conduct the fizz experiment was that prior greenhouse experiments (Mauney and Hendrix, 1988) have shown large increases in cotton yield when irrigated with fizz water, and a field experiment was needed to determine whether such a treatment would be a practical means to improve cotton yields. The 1986 results were encouraging with about an 11% increase in seed cotton yield (when the yield of 1 abnormally productive control plot was ignored), but additional confirmation was badly needed. The FACE experiment in 1986 was similarly encouraging with about a 22% increase in seed cotton yield, but prodigious amounts of CO_2 were required to enrich for 11 hours per day from 06:00 to 17:00. Therefore, in 1987 the daily enrichment was reduced to 4 hours per day from about 10:30 to 14:30 which was approximately symmetrical about solar noon, when it was felt that enrichment would be most effective under the highest solar radiation levels.

OPEN-TOP CHAMBER CO_2-WATER-NITROGEN EXPERIMENT ON COTTON

A. Materials and Methods

1. Culture of the experimental crop

The cotton crop was grown on the field just west of the Western Cotton Research Laboratory, Phoenix, Arizona, on identically the same plots as the 1986 experiment (Kimball et al., 1986). A plot plan is shown in Figure 1. The soil is Avondale clay loam (Fine-loamy, mixed (calcareous), hyperthermic, Anthropic Torrifluvent). Following the 1986 experiment, all equipment was removed from the field, and it was tilled and planted to a winter crop of barley. The barley was cut and removed from the field before it was mature. There were obvious differences in barley growth among the plots indicative of the CO_2-water-nitrogen treatments of the summer before. The main purpose of the barley crop and of placing the 1987 plots on exactly the same spots as the year before was to make the "none-added" nitrogen treatment be as severe a low fertility treatment as possible.

After removal of the barley crop, the field was disked and ploughed into ridges and furrows at the beginning of April. A preplant herbicide, Prowl[1] (diuron) was applied at a rate of 1 pint/acre on 4 April 1987. Using a two row planter, cotton (Deltapine-61) was planted on 7 April 1987. The planting was done on the top of raised beds with a furrow between each row spaced 1.016 m (40 in.) apart. Following planting, neutron access tubes were again installed as in 1986, and again the gravel layer restricted their possible length in the more northern plots. Open-top chamber construction started on 13 April, using the same design as before, and was mostly completed by 16 April, including installation of the same drip irrigation system with the tubes placed next to the plants in each row. Starting the afternoon of the 16th and continuing all night, a large (89-144 mm) irrigation was applied to all the plots (Table 1). The seed was sprouting by the 20th, but there was some crusting of the soil surface, so a light irrigation (12-18 mm, Table 1) was applied to all the plots on 23 April. The tops of the beds were manually raked off in places where the cotton was planted particularly deep, and by the 24th at least 50% of the plants were emerged. Transplants were used to fill some gaps on 29 April, and another light irrigation (14-22 mm, Table 1) was applied to all plots on 30 April. Additional transplanting and an additional light irrigation were applied on 4 and 5 May, respectively. The plants were thinned (along with a few more transplants to fill some persistent gaps) to a uniform 10 per meter or 100,000/ha on 8 May, the same day the CO_2 enrichment treatment was started.

To prevent some of the insect problems experienced in 1986, Temik was applied along the rows in the chambers on 8 May. An aggressive insec-

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[1] Trade and company names are mentioned for the benefit of the reader and do not imply preferential treatment or endorsement of the products listed by the U. S. Department of Agriculture.

ticide application program was followed in 1987 (Table 2), and insect damage was minimal.

2. Irrigation and water use

As already mentioned the same drip irrigation system was used as in 1986, which had emitters (2 l/hr at 10 m of head) spaced every 0.25 m. After stand establishment, the same formula, Equation 1, was again used to calculate the amount of water to apply weekly (usually Tuesdays) to the well-watered ("wet") plots:

$$\text{irrigation amount} = \text{pan evaporation} \times (\text{LAI}/3) \qquad (1)$$

where LAI is the leaf area index projected from the previous week's destructive plant harvest. Above a LAI of 3, the irrigation amount was the pan evaporation amount of the previous week. The pan evaporation was the amount of water that evaporated from a Class A pan located beside the field during the previous week. The dry or water-stressed plots received 2/3 of the amount of water applied to the wet plots.

Rainfall was measured from a gauge beside the field, and the rainfall amounts were subtracted from the calculated irrigation requirements each week. Also, any shortage (or excess) of the actual amount applied from the target application for a particular week was added (or subtracted) from the target application for the next week.

The irrigation system was split into four sections: wet-N^+, wet-N^-, dry-N^+, and dry-N^- plots each being irrigated together. The amounts of irrigation and rainfall applied to the irrigation blocks are given in Table 1 and Figures 2 and 3, along with the "consumptive use" curves of Erie et al. (1981). The amount applied deviated from Erie et al. early in the season because of the initial stand-establishment irrigations. Then on 16 June there was a failure of an irrigation timer plus a break in a pipe connection resulting in too much water being applied to the wet-N^- plots. To treat all the wet plots as nearly alike as possible, it was then decided to give additional water to the wet-N^+ plots also; then there was another problem with pipe connections in the wet-N^+ plots. The result was that all wet plots were over-irrigated on about day 170, which caused the abrupt jumps above the Erie et al. curves then (Figures 2 and 3), but subsequent irrigations were close to the target amounts so the irrigation curves parallelled the Erie et al. curves for the rest of the season. Fortunately, there was no problem with the irrigation system in the dry plots, and they experienced a water deficit for most of the season.

The total water use for each of the plots is presented in Table 3. The change in soil water storage between 16 April and 9 October was calculated from neutron soil moisture storage measurements made on those dates. The wet plots gained an average 23 mm from storage over the season (ignoring any that might have been lost below the root zone during the season), whereas the dry plots were an average 84 mm drier at the end of the season. There were no consistent differences in water use associated with the CO_2 treatments. Compared to the amounts of water applied by irrigation and rainfall, the soil storage changes were very small (-1.7% for the wet plots and -8.1% for the dry plots). Therefore, the total water use was very close to the total amount of water applied.

3. Nitrogen applications and uptake

Before planting and after harvest soil samples were taken from each of the plots for analysis of NO_3^--N and total N. Using an Oakfield probe, core samples were taken from 2 within-row and 2 between-row sites in each chamber from 0-150, 150-300, and 300-600 mm depths. The soil from the same depth increments in each chamber was composited, and a subsample was saved for analysis. The specific ion electrode method was used to determine NO_3^- following extraction with $CaSO_4$ (Keeney and Nelson, 1982), and the regular Keldahl method was used for total N (Bremmer and Mulvaney, 1982).

Starting on 2 June, urea was injected into the irrigation water applied to the N^+ plots. The urea was dissolved into about 15 liters of water to make a stock solution, which was injected into the irrigation pipe using a commercial water-pressure-driven suction device. The actual injection took about half an hour near the middle of each irrigation with unfertilized water passing through the system before and after each injection. Starting on 14 July, a switch was made to Uran-32, which supplies readily available NO^-_3-N, as well as NH_4^+-N (Table 4). The nitrogen applications are summarized in Table 4, with the seasonal total being 231 kg N applied per ha. The results of the soil nitrogen analyses are presented in Table 5. The nitrate-N contents of the dry plots appeared to be somewhat higher, but there was no obvious effect of the CO_2 treatment or, surprisingly, of the nitrogen added treatment. The decreases in nitrate-N content from beginning to end of the experiment were not consistent, and in many plots, the contents actually increased. However, the changes were small compared to the 231 kg/ha added to the N^+ plots.

The total-N analyses (Table 5) also were not helpful in determining the amount of N available from the soil during the course of the experiment. The "background" N in the soil organic matter was simply too high for such a soil analysis technique.

4. Carbon dioxide concentrations

The CO_2 concentrations were again continually monitored with the automatic sampling/control system, as described previously (Kimball et al., 1983, 1984, 1985, 1986). The diurnal patterns of mean CO_2 concentrations for the 1987 experiment are presented in Figures 4-7. Like previous years, the ambient concentrations underwent a diurnal variation from about 350 $\mu\ell/\ell$ in daytime to about 400 $\mu\ell/\ell$ at night. The enriched plots also exhibited some diurnal variation, but it was less pronounced because of the controlled set point at 650 $\mu\ell/\ell$. After sunrise each day, the concentrations decreased below set point for an hour or two until the system responded to the higher level of atmospheric turbulence. After sunset, concentrations rose above set point until the system similarly adjusted to calmer night conditions.

The overall CO_2 concentration means and standard deviations of the individual observations are tabulated in Table 6. In 1987, they averaged 344 ± 40 and 630 ± 79 $\mu\ell/\ell$ during daytime, 385 ± 57 and 651 ± 83 during nighttime, or 363 ± 52 and 639 ± 82 averaged over a whole (24 hr) day for the ambient and "650" treatments, respectively.

An independent check of the chamber CO_2 concentrations was performed in 1987, and these results are presented in Table 7. A Li-Cor Model 6200 portable photosynthesis system was used to measure leaf photosynthesis about twice a week for much of the season. The sampling procedure is described in more detail later, but briefly, starting about 10:00 on each sampling day, photosynthesis measurements were taken sequentially in each chamber. The air in each chamber was analyzed for CO_2 concentration using this system as part of the measurement. Within each chamber, three leaves were measured near the top of the canopy of the middle row starting first near the door and progressing toward the back. The mean absolute CO_2 concentrations recorded during the course of each photosynthesis determination (the CO_2 concentration declined a few $\mu\ell/\ell$ during the course of each measurement) were recorded, compiled, and subjected to an analysis of variance (Table 10, Kimball et al., 1986). As expected, day-of-year was a highly significant factor as windiness varied from day to day, but this was of no special interest, so the data were averaged for the season. Also as expected, neither irrigation nor nitrogen nor reps significantly affected the CO_2 concentrations, so the results were averaged over these factors for presentation in Table 7.

Two surprises appear in the "Li-Cor" CO_2 concentrations in Table 7. First, the CO_2 concentrations were higher than the daytime concentrations recorded by the control system (Table 6). The 12 $\mu\ell/\ell$ increase in the ambient levels can easily be attributed to the operator's breath. However, the 76 $\mu\ell/\ell$ increase recorded for the enriched chambers is perplexing. Also puzzling is the fact that the leaf factor was significant. The first leaf measured in each enriched chamber, which was closest to the door, was exposed to an average CO_2 concentration of 753 $\mu\ell/\ell$. Progressing inward the concentrations decreased to 708 and then to 653 $\mu\ell/\ell$, the latter being the set point for the chamber. What could cause the difference between the data in Tables 6 and 7, and which to believe? In prior testing of chamber performance, no such difference was detected, but prior tests were comparatively spotty and did not involve as many systematic measurements. In order for both data sets to be correct, we can speculate (1) that there may have been a preferential flow of CO_2-enriched air toward the front of the chambers caused by the forward momentum of the air leaving the perforated distribution tubes, and (2) that the air sampling manifolds may have been preferentially sampling toward the back of the chambers closest to the pumps. The data in Table 7 are based on a few hundred measurements, whereas those in Table 6 involve many thousands, so it is difficult not to believe the Table 6 measurements from the sample/control system. Nevertheless, these independent portable photosynthesis system measurements suggest there may have been an average systematic underestimation of the enriched chamber CO_2 concentrations of about 60 $\mu\ell/\ell$.

B. Results

1. Leaf area, flower production, boll retention, biomass and yield

The daily flower counts, boll load and rate of boll retention were obtained from daily tagging of the center row within the enclosures. Tagging was performed five days each week. The boll loading for the weekends was estimated by interpolation of the rates on the adjacent Fridays and Mondays.

Destructive harvests of 3 plants from the outside rows were done weekly through the season. However, to reduce the impact of so much removal of plant material on the remaining plants, the samples were only taken from one Rep at a time, alternating each week. Thus, Rep I was sampled one week and Rep II was sampled the next for twelve weeks of the season. Plants chosen for the intermediate harvests were taken from the outside rows of the three rows within a chamber so as not to disturb the center which was reserved for the final harvest row. The plants selected for harvest were chosen because they represented the average stem diameter for that treatment. They were removed from a different quadrant of the chamber each week, thereby thinning the plant population in that quadrant but not producing a gap so that the "border" effect of that row upon the center row was preserved.

Counts were made on the harvested plants of the numbers of squares, flowers, bolls, and abscised sites. The plants were separated into roots, stems, leaves, and bolls, and the dry weights of each were determined. Leaf area was also measured and leaf area index (LAI) and leaf area per active boll (LA/B) were computed.

The final harvest on 15 October 1987 was from the three meters of center row in each chamber. Green bolls on the date of harvest were counted and an estimate of their final weight of seed cotton was calculated. It was assumed that these bolls would have achieved 80% of the weight of the open bolls.

Final yield and yield components for 1987 are shown in Table 8. In 1987 there was a pronounced effect of N on the productivity of both the ambient and 650 $\mu\ell/\ell$ CO_2 (C^- and C^+) treatments with an average seed cotton yield reduction of 29% in the low N plots. In spite of marked decrease in yield with the severe low N fertility treatment in 1987, the response to CO_2 was substantial, averaging 37 and 52% for the wet and dry treatments, respectively. Though the absolute productivity of the $WetC^+N^+$ treatment was the greatest of all treatments, the relative effect of CO_2 was greatest in the stressed treatments. That is, $DryC^+N^-$ was 52% greater than $DryC^-N^-$ while $DryC^+N^+$ was 43% greater than $DryC^-N^+$. Similarly, $WetC^+N^-$ was 37% greater than $WetC^-N^-$ while $WetC^+N^+$ was only 25% greater than $WetC^-N^+$.

The $DryC^+$ treatments averaged a 48% increase in seed cotton due to CO_2 enrichment, while the $WetC^+$ treatments averaged only 31% over their $WetC^-$ counterparts. The seed cotton data for 1987 are plotted in Figures 8 and 9, and the lack of CO_2 response for the Rep II-$WetN^+$ and Rep II-$WetN^-$ plots is striking (Figure 9) in comparison to the other reps and treatments. Referring to the biomass (dry weight) data in Table 8, the growth in the Rep II-WetN$^-$ plot was inconsistently low. The growth in the Rep II-WetN$^+$ was comparable to Rep I, but the harvest index for this plot was the lowest of all the plots. Focusing on the harvest index data in Table 8, except for the Rep II-WetN$^-$plots, all of the CO_2-enriched plots had lower harvest indices than their ambient counterparts. This result is different from prior years of this experiment which showed no effect of CO_2 on cotton harvest index.

Progress of the crop as boll load, flower counts and boll retention for the nitrogen-added (N$^+$) treatments are shown in Figures 10, 11, and 12 and for the no-nitrogen-added (N$^-$) treatments in Figures 13, 14, and 15. As in previous years, the boll loading pattern in all treatments was cyclic (Figures 10 and 13). The degree of the CO_2 effect was influenced by the stage of the season. For N$^+$ treatments, (Figure 10), there was very little effect of Dry except for the time period 200-210. For the N$^-$ treatments, almost all the effects of CO_2 and of water were evident by day 190 (Figure 13). Greater flower production during days 170-190 (Figure 14) was primarily the cause of the greater boll load.

The leaf area index and leaf area per boll data are shown in Table 9. The early boll loading in all these chambers is evident from the very low LA/B by day 174. Cutout was evident in the nitrogen stressed (N$^-$) treatments because the LA/B increased at day 209-223 before additional boll setting reduced LA/B at day 230.

The accumulated seed cotton yield data from five seasons' CO_2 enrichment experiments in open-top chambers at Phoenix, Arizona are presented in Figures 16 and 17 and Table 10. The large response of cotton to CO_2 is obvious. Referring to Figure 17, the lack of CO_2 response of the Rep II-WetN$^+$ and Rep II-WetN$^-$plots for 1987 appears even more inconsistent here than in Figure 9. Performing a linear regression analysis on all the data in Figure 17, results in the equation shown with an average 64% increase in yield at 650 $\mu\ell/\ell$ of CO_2. Turning to Table 10, a near-doubling of CO_2 has produced an average yield increase of 56% under well-watered and fertilized conditions. Under conditions of water stress, the response has been larger, averaging 74%. In contrast to some prior nutrient solution studies in the literature (Kimball, 1986), there was a large response to CO_2 even under low nitrogen conditions, averaging 53%.

2. Petiole NO_3^- nitrogen analyses

All of the treatments dramatically affected the petiole NO_3^- nitrogen concentrations, as shown in Figures 18 and 19 and Table 11. As expected, the added-nitrogen (N$^+$) treatment significantly increased the NO_3^- concentrations, and the concentrations in the no-added-N (N$^-$) treatment would generally be regarded as deficient (Soil Improvement Committee, California Fertilizer Association, 1985). Apparently the strategies of growing a winter barley crop and of locating the plots in exactly the same places as in 1986 were indeed effective in producing a nitrogen stress treatment. The 650 $\mu\ell/\ell$ CO_2 treatment had lower petiole N concentrations than the ambient treatment, which we interpret to mean that the high CO_2 plants had a larger N requirement which depressed the petiole NO_3^- -N levels. Several interactions were significant. Probably the most important to note is that of CO_2 x Nitrogen (Table 11). The depression of the petiole NO_3^- concentrations by high CO_2 was large for the N+ treatment but statistically insignificant for the N- treatment. The first order interactions with biweeks through the season were significant also, as can be seen by the tendency for the ambient-WetN+ and the 650-WetN+ values to increase through the season (Figure 18) and for the ambient-DryN- values to decrease through the season (Figure 19).

3. Leaf photosynthesis, stomatal conductance, and foliage temperatures

Net leaf photosynthesis and stomatal conductance were measured at midday in all of the open-top chambers on several clear days during the 1987 growing season using a Li-Cor Portable Photosynthesis System. Over the winter the System was upgraded from the Model 6000 used in 1986 to a Model 6200 which was more stable and required a shorter time for the leaf chamber to be clamped on a leaf before a reading could be obtained. The shorter time was generally about 10 seconds (determined by internal software) compared to the 20 seconds last year. However, it still took a few seconds for the CO_2 concentration to begin a steady decline before the actual data logging began.

The measurements were usually taken 2 days and again 6 days following the weekly irrigations. Therefore, those taken 2 days after irrigation were regarded as being unstressed for water. The weather patterns and rainfall during each week were noted and those 6-day-after-irrigation data that were obtained during weeks when the weather was mostly clear were selected for further analysis as representative of water stress conditions, particularly for the dry irrigation treatment.

An infrared thermometer was carried along with the photosynthesis system, and immediately upon entering a chamber, 10 foliage temperature readings from both the west and east sides of the center row were taken and recorded using a polycorder. Then net photosynthesis and stomatal conductance were measured on three leaves in the center row of each chamber starting near the door. Generally, the youngest, fully-expanded leaves in full sunlight were chosen for measurement.

The net photosynthesis results are presented in Figure 20 and Table 12. In the 2-day-after-irrigation data in the bottom of Figure 20, the CO_2 treatment obviously stimulated photosynthesis. Averaging over the whole season, the increase was a significant +45% (Table 12). But it is difficult to perceive any effect of the irrigation and nitrogen treatments. Since the measurements were taken only 2 days after the irrigations were applied to the field, any water stress in both the wet and dry treatments should have been relieved, so it is not surprising that irrigation had no significant effect on these photosynthesis data. In 1987, the nitrogen stress treatment was fairly severe (Table 11) and yield was decreased (Table 8), so some effects on photosynthesis would be expected. However, the photosynthesis of the N+ treatment was only slightly higher than the N- treatment (Table 12), which approached but did not achieve significance (0.063 probability level). Also, there was a significant effect of day-of-year on the net photosynthesis, as usual.

However, there was no gradual decline through the course of the growing season, as was observed in 1986 (Kimball et al., 1986), so possibly the decline in 1986 was due to the greater insect and virus problems experienced that year.

Considering the 6-day-after-irrigation data in the top of Figure 20, there is considerably more scatter. On some days there obviously was a depression of photosynthesis with the dry treatment, but considering all sampling days, the average decrease was only 9% (30.4 compared to 33.4 in Table 12). There was no apparent effect of the nitrogen treatment. On the other hand, CO_2 enrichment continued to stimulate photosynthesis on most of the days, averaging 54% over all the sampling days.

The stomatal conductance results are presented in Figures 21 and 22 and Table 13. During June, a temperature sensor in the portable photosynthesis system was malfunctioning, thereby making the conductance data unreliable but having little effect on the photosynthesis data. The instrument was repaired the last week of June, but as a result of the problem, there are data for more sampling days presented for photosynthesis than conductance. For most days the "raw" conductance values as computed by the instrument averaged about 2 cm/s for the 2-day-after-irrigation data (Figure 21). However, on days 218 and 232 the values were considerably higher for no apparent reason. Lacking any physical reason to exclude them, they were considered part of the data set, obviously making day-of-year a significant factor.

Focusing first on the raw 2-day-after-irrigation data (Table 13), the nitrogen treatment had no significant effect, so for simplification, the data in Figure 21 were averaged over nitrogen (as well as reps and leaves). Like the photosynthesis data, there was no effect of the irrigation treatments in these data collected only 2 days after the irrigations were applied. CO_2 enrichment, on the other hand, caused a partial stomatal closure (20% decrease, Table 13), which was statistically significant and was about the same magnitude as in 1986 (Kimball et al., 1986).

In 1986 (Kimball et al., 1986) there was a distinct decrease in stomatal conductance near the end of the season, when the summer monsoon ended and temperatures abruptly dropped. There is only a slight hint of such a pattern in the 1987 data (Figure 21). However, the 1987 data did not extend as late into the fall and the 1987 monsoon lasted longer than normal. Temperatures did not decline nearly as much at the end of the season in 1987 as they did in 1986 (Figure 23), so this is further evidence that the late summer decrease in conductance in 1986 was in fact a temperature response, as opposed to a stage-of-growth phenomenon.

Considering next the raw 6-day-after-irrigation data (Figure 22 and Table 13), the stomatal conductances were about half of the 2-day-after-irrigation values. As expected, the nitrogen treatment again had no significant effect. The CO_2-enrichment treatment continued to reduce conductances by about 17%, although the difference was not quite statistically significant (0.066). It was expected that the conductance of the wet treatment would be higher than the dry 6 days after irrigation, and the means indicate such was the case, but the difference was not statistically significant. However, the experimental design had low resolution (few degrees of freedom, Table 10, Kimball et al., 1986) for the irrigation treatment.

It has often been reported that stomatal conductance decreases with decreasing humidity of the air. In contrast to this body of data stand numerous observations of canopy temperature with infrared thermometers, which show progressive cooling of the crop below air temperature with decreasing humidity, and these crop temperature data give no hint of stomatal closure with decreasing humidity. Idso et al. (1987) attempted to resolve the discrepancy. They postulated that the rapid air movement caused by the fans in the leaf chambers caused the dry air to impinge close to the stomata, causing their rapid partial closure, whereas in the open field, the dry air above the crop was sufficiently insulated by higher humidity next to the plant leaves that the stomates seldom close in response to low air humidity at the measurement level above the crop. They recommended an adjustment procedure that utilizes infrared temperature measurements of the "free-air" crop canopy just before the leaf chamber is clamped on a leaf for the conductance measurement. Accordingly, the stomatal conductance measurements were all adjusted following their recommended procedure. The procedure involves the calculation of a mean stomatal conductance and a mean "IJ index" for the leaf chamber. For the purposes of this analysis, separate means were computed for each CO_2-irrigation-nitrogen treatment combination, the averaging being done over reps, sampling days, and leaves.

The adjusted results are also presented in Figures 21 and 22 and Table 13. The adjusted values were roughly double the raw values. Whether the raw or the adjusted values are a truer representation of nature awaits further testing of the procedure of Idso et al. (1987). In the meantime, the statistical analyses of the adjusted data yielded results and conclusions that were very similar to those of the raw data (Table 13).

The 1987 foliage temperature data are plotted in Figure 24, along with data from prior years (Kimball et al., 1983, 1984, 1985, 1986). All of these data were obtained under clear sky conditions 2 days following an irrigation. Thus, even the plants in the "dry" plots should not have expressed much influence of instantaneous water stress. The CO_2 concentrations used for plotting the 1987 data were those measured by the Li-Cor Portable Photosynthesis System shortly after the infrared foliage temperatures were recorded. As discussed previously, the concentrations measured by the Li-Cor were somewhat higher than the desired set point (Table 7), and the wet-N^+ point for 1987 is particularly high, about 765 $\mu mol/mol$ (or $\mu \ell/\ell$). The data for 1987 appear to be consistent with the curve that was fitted to the 83-85 data previously, even the high wet-N^+ point. The main deviations from the curve are the "dry" points for 1986, which exhibit about the same foliage temperature increase to CO_2 in spite of the ambient-dry being about 1.4 C warmer than the ambient-wet. In 1987 the dry-N^+ data again show about the same temperature increase with increasing CO_2, but in contrast to 1986, the foliage temperatures were cooler rather than warmer than those in the corresponding wet plots. Thus there appears to be some inconsistency about the way the temperature of the plants in the dry plots adjusts following an irrigation. Nevertheless, the response of the foliage temperature to CO_2 has been quite consistent, and we have again confirmed that an increase in CO_2 concentration of about 300 $\mu\ell/\ell$ will increase the foliage temperature of non-water-stressed cotton by about 1.0 C.

4. Canopy net photosynthesis and light response curves

In the preceding section, data were presented showing that CO_2 enrichment increased net photosynthesis of cotton leaves about 50%. Similar data were obtained in prior years of this project. However, all of these measurements were taken on the youngest fully-expanded leaves, which may not have been representative of the cotton canopy as a whole. Therefore, an attempt was made to measure whole canopy net photosynthesis in order to establish the relative magnitudes of the leaf and canopy net photosynthesis rates.

Measurement of canopy net photosynthesis proved to be difficult. Using the technique of "chimney-tops", as was done by Drake et al. (1987), it eventually was possible. The basic technique was to mount a pyramid-shaped roof with a chimney on the chambers, which normally had open tops, and then measure the change in CO_2 content of the air as it passed through the chamber.

The pyramid-shaped roofs consisted of a frame of light-weight aluminum tubing covered with transparent polyethylene film. The tubing (nominal diameter of 1/2 inch) was the type normally used for electrical conduits. The chimney tops had a square base about 2.8 m on a side, which would easily fit within the 3 m square open-top chambers. The sides went up at an angle of about 45 degrees to a smaller square that truncated the top of the pyramid shape. The smaller square was 0.6 m on a side. Then rising from the smaller square was a chimney which itself was square in cross section. The final height of the chimney itself was 1.5 m. The polyethylene film (6 mil, 0.15 mm thickness) was the same material used in walls of the chambers themselves. It was fastened to the frame using 100-mm-wide strips of transparent tedlar tape (PT-100-C, Flexcon Co., Albuquerque, NM). A flap of polyethylene film about 0.4 m wide extended all around the outside of the bottom square base.

To mount the chimney-top on a chamber, two persons would lift the chimney-top above their heads and walk it across the wall of a chamber. Then they would lower the base of the chimney-top into the chamber just slightly below the tops of the chamber posts. The chimney-top was then suspended from the corner posts using loops of wire. The outside flap was flipped up over the chamber walls and then secured to the outside of the walls using tape. Large paper clips were also used to fasten the flap to the chamber walls. Any holes were covered with the tedlar tape. The door to the chambers was also sealed by fastening folds of the plastic walls with additional large paper clips.

Two such chimney-tops were constructed, and they were used as a pair. On the evening before a measurement day was anticipated, they were installed on ambient and 650 $\mu\ell/\ell$ chambers (well-watered and nitrogen-added treatments) of Rep I or Rep II (Figure 1). Then on the following day starting at dawn, canopy and leaf photosynthesis measurements were taken alternating each hour through the day between the two chambers with the chimney-tops. At the end of the day, the tops were removed from the chambers and installed on the other Rep to be ready for the following day (or they were removed completely). The tops were never left on any chamber for more than a day at a time in order to minimize any effect of the slightly changed environment under the chimney-top, as compared to an open top.

A pair of black polyethylene sampling lines (64 m long, 3.18 mm inside dia., 6.35 mm outside dia.) were strung to each chamber being measured, and sampling pumps were installed in the lines about 3 m from the intake ends. The intake for one line was positioned in the duct delivering air to the chambers, and the intake of the other was placed in the chimney but only about 0.2 m from the chimney bottom. To damp the fluctuations in CO_2 concentration, 2 glass 3.785 ℓ (1 gal.) jugs were installed in series in each sampling line, as was done by Drake et al. (1987). Flow meters were also installed in the lines, and valves were used to adjust the flow to identical 1.0 ℓ/min. rates. The total jug plus sampling line volume was 8.1 liters, which gave a time constant of 8 min. Of course, with the mixing of the sample streams in the jugs, the equilibrium time of the outlet adjusting to a new concentration at the inlet was several times 8 min. The sample pumps ran continuously, so that "fresh" as possible sample air came out the outlet end. Therefore, as the measurements alternated hour by hour between the ambient and enriched chambers, there never was stagnation of the sample air in the lines.

The change in CO_2 concentration of the air passing through the chambers was measured using an ADC Model MK3 infrared CO_2 analyzer in differential mode. At the start of each hour, the analyzer was calibrated by passing a 501 $\mu\ell/\ell$ primary standard (Matheson Gas Products, Cucamonga, CA) through both sample and reference sides to zero the analyzer. Then zero CO_2 gas was passed through the small cell, which was designed to provide a 5% (or 25 $\mu\ell/\ell$) differential to adjust the span. During a run, an Omnidata Polycorder was used to continually measure the analyzer output voltage at about 4 sec. intervals, compute the differential CO_2 concentrations, and then display the average at the end of the run.

The rate of air flow through the chambers was measured using a Taylor propeller anemometer. The instrument was positioned about 1/3 of the way across the chamber in one of the perforated lateral distribution tubes. Then a series of three measurements was taken at that position and averaged. The result was scaled up in proportion to the ratio of the total number of holes in the tube to the number downstream from the anemometer and then multiplied by the cross-sectional area of the tube. The procedure was repeated for all four laterals, and their individual flows were added to get the total for a chamber (Table 14).

The canopy photosynthetic rates were computed using the following equation:

$$P = (\Delta C)\ F\ K/A$$

where P is the photosynthetic rate (μmol m^{-2} s^{-1})

ΔC is the change in CO_2 concentration through the chamber ($\mu\ell/\ell$)

F is the air flow rate (m^3/s)

A is the area of the chambers ($9.3\ m^2$), and

K is a units conversion factor with temperature and pressure corrections

$$K = [1 \mu mol\ CO_2/22.4\ \mu l\ CO_2][273°C/(T_D + 273°C][97.36\ kPa/101.33\ kPa][10^3\ l\ air/m^3\ air]$$

where

T_D is the measured dry bulb temperature (°C) and 97.36 kPa is the average barometric pressure for Phoenix.

During the course of the canopy photosynthesis measurements, the solar radiation conditions varied from near zero to full noon-time sunshine, but attenuated by the chimney tops. To be able to account for the attenuation, the average photosynthetic photon flux density (PPF) as measured by the Li-Cor Portable Photosynthesis System from the 10 leaf measurements (but outside the leaf chamber) within each hour was plotted against the hourly average (roughly 60 observations per hour) PPF as measured by the automatic data acquisition system with the pyranometer on the outside weather mast. The pyranometer was calibrated in W/m^2 of total spectrum solar energy, and to convert to PPF in $\mu mol\ m^{-2}\ s^{-1}$, the energy flux values were multiplied by 2.3 [using a value of 4.6 to convert from W/m^2 of photosynthetically active radiation to PPF in $\mu mol\ m^{-2}\ s^{-2}$ from Li-Cor (1982) and assuming 0.50 for the fraction of solar radiation that is in the 400-700 nm band from Monteith (1973)].

The PPF values measured by the Li-Cor inside are plotted against the corresponding readings from the outside weather mast in Figure 25. There is considerable scatter, which is to be expected since the inside values were averages of 10 instantaneous measurements near the middle of each hour, whereas the outside values are hourly averages of about 180 readings. The technicians tended to point the leaves toward the sun which might have caused the inside PPF values to be somewhat too high (compared to horizontal) early in the morning and late afternoon, but the data points at low PPF tend to be below the regression rather than above. Therefore the slope of the linear regression line forced through the origin (0.769) was taken as the transmittance of the chimney tops.

The transmittance of the leaf chamber was also measured. It was the 1 liter model manufactured by Li-Cor with a Lexan top. The quantum sensor of the Li-Cor Model 6200 Portable Photosynthesis System was detached. Then readings were taken with the sensor pointed toward the sun without and with the leaf chamber top above the sensor, and the transmittance was determined to be 0.81.

The canopy net photosynthesis measurements are presented in Figure 26 as a function of photosynthetic photon flux for both the ambient and the 650 $\mu\ell/\ell$ CO_2 treatments. There is considerable scatter in the data, resulting in r^2 values of only 0.75 and 0.51 for the quadratic regression curves from the ambient and 650 $\mu\ell/\ell$ CO_2 treatments, respectively (Table 15). At a PPF of 1500 $\mu mol\ m^{-2}\ s^{-1}$, the percentage increase due to CO_2 computed from the regression equations was +51%, which was only slightly more than the increase in midday leaf net photosynthesis averaged over several days during the season (Table 12). Also plotted is a net photosynthesis curve from Baker et al. (1987) which was used to develop the photosynthesis subroutines used in the cotton growth model GOSSYM. The curve for a temperature of 30 C and a vapor pressure deficit of 1 kPa (and ambient CO_2) was taken because these conditions were similar to those in the chambers at the time of the canopy photosynthesis measurements. The data from the study appear slightly higher than the Baker et al. curve at the higher photon fluxes, but in general the agreement is quite good.

The leaf net photosynthesis data obtained at the time of the canopy measurements are plotted in Figure 27 against the PPF measured by the Li-Cor and adjusted for leaf chamber transmittance. Each point is the average for 10 leaves. The scatter in these data is small with r^2's of 0.96 and 0.90 for the quadratic regression on PPF for the ambient and 650 chambers, respectively (Table 15). The percentage increase at 1500 $\mu mol\ m^{-2}\ s^{-1}$ due to CO_2 is only +27%, however, which is about half the increase in midday leaf photosynthesis averaged over several days during the season (Table 12).

Leaf area measurements were taken periodically through the season (Table 9), and the values from 18 and 25 August, the dates closest to the canopy net photosynthesis measurements were used in the analysis (Table 14). The LAI's from the two ambient chambers were 2.77 and 2.53, while those from the 650 chambers were 2.99 and 1.93 (Table 14), which was somewhat inconsistent. Nevertheless, the leaf net photosynthesis values were multiplied by the LAI of the chamber from which they were obtained, and these data are presented in Figure 28. The degree of scatter was comparable to that of the original leaf net photosynthesis measurements alone (Figure 27, Table 15), but scaled upward. At a PPF of 1500 $\mu mol\ m^{-2}\ s^{-1}$, the increase due to CO_2 was relatively smaller, about +19%.

To facilitate comparison without the clutter of all the data points, the regression curves from Figures 26, 27, and 28 are replotted together with the Baker et al. curve in Figure 29. The canopy net photosynthesis curves are slightly higher than the corresponding leaf curves from about 500 to 1600 $\mu mol\ m^{-2}\ s^{-1}$ photon flux, and then they bend below the leaf curves at photon fluxes below and above this band. The leaf curves do not appear to saturate at high PPF, so it is somewhat surprising that the canopy data suggest such a tendency. Considering the amount of scatter in the canopy photosynthesis data and that the Baker et al. curve is still increasing 1700 $\mu mol\ m^{-2}\ s^{-1}$ photon flux, probably not much credence should be given to this apparent saturation of canopy net photosynthesis at high photon flux.

The most striking feature of Figure 29, however, is that the canopy and leaf curves really corresponded closely for the two respective CO_2 levels. The "X LAI" curves in Figure 29 show what the canopy net photosynthesis rate would have been if there were no shading of lower leaves, no decline in leaf photosynthetic rates with leaf aging and similar canopy and leaf respiration rates. Thus, the additional leaf layers that gave LAI's from 1.93 to 2.99 (Table 14) almost exactly compensated for mutual shading and leaf aging, and differences in respiration, so that canopy net photosynthetic rates were about the same as those of the youngest, fully-expanded leaves at the top of the canopy.

Next, the two leaf light response equations for the ambient and 650 CO_2 levels (Table 15) were used to adjust the leaf net photosynthesis values upward to account for the cuvette transmittance of 0.81. First "predicted" photosynthesis rates were computed using measured PPF values in the equations, and then "adjusted-predicted" rates were computed using the measured PPF values divided by 0.81. Then the difference between the two predicted photosynthetic rates was added to the original measured leaf photosynthesis rate (which was an average from 10 leaves) to obtain an adjusted rate for each of the original data points.

After adjusting for cuvette transmittance, the leaf and canopy net photosynthetic rates could be directly compared, as is done in Figure 30. There is considerable scatter, and a linear regression of canopy on leaf net photosynthesis could account for only 49% of the variance. However, the slope is close to 1.0, which again suggests that additional leaf area (above a LAI of 1.0) compensated for the effects of mutual shading and leaf aging. Thus, it appears that it is reasonable to assume that our prior measurements of leaf photosynthesis on young fully-expanded leaves at the top of the canopy were reasonably representative of the canopies as a whole.

5. Leaf starch content

To test the effect of irrigation cycle water stress, nitrogen fertilization and atmospheric CO_2 enrichment (Tables 1-7) on cotton leaf starch, leaves in the CO_2 chambers were sampled twice during the weekly watering cycles. Leaf samples were taken two days following irrigation (least weekly water stress) and six days following irrigation (greatest weekly water stress). The same leaves were sampled at dawn and at dusk to determine the diurnal fluctuation in leaf starch. These sampling times correspond to the daily minimum and maxima, respectively, of cotton leaf starch (Hendrix and Huber, 1986; Hendrix and Grange, 1988). As in 1986 (Kimball et al., 1986), the samples consisted of six 0.28 cm^2 disks that were punched along the leaf margin avoiding any large veins. The leaves chosen for sampling were mature, fully expanded, and exposed to full sun near the top of the canopy. The leaf punches were collected into ice-cold 80% ethanol and quickly transferred to a -80°C freezer for storage prior to analysis by an enzymatic technique (Hendrix and Peelen, 1987). Leaf samples were extracted by grinding in 80% ethanol and the residue repeatedly extracted with hot (80°C) 80% ethanol. The alcohol-insoluble residue was next digested with amyloglucosidase (Brown and Huber, 1988) which quantitatively converts starch in the ethanol-washed residue to glucose. The glucose released by this treatment was determined from the absorbance change due to the conversion of NAD to NADH in a coupled glucose-6-phosphate dehydrogenase assay (Hendrix and Peelen, 1987).

Compared to the plants grown at ambient CO_2 with no added nitrogen and under water-stress (C-N-W-, Fig. 31), supplying adequate water (C-N-W+, Fig. 32) or nitrogen (Fig. 33) by themselves had no significant effect on starch accumulation patterns in open-top-chamber-grown cotton leaves.

However, increasing carbon dioxide alone did have a significant effect on both the AM and PM levels of leaf starch (C+N-W-, Fig. 34 vs. Fig. 31). Although this treatment caused a dramatic increase in leaf starch in these plants, it is interesting to note that the AM starch levels are almost identical to these in the PM. This indicates that this increase was not leading to an increased export of this carbon to the rest of the plant (cf. the FIZZ/FACE starch discussion which follows). It appears as if more starch was created in the leaves, but because the plants lacked sufficient nitrogen and water to use the additional starch, it simply accumulated in the leaves. A similar buildup in cotton starch has been observed when they were deprived of water and phosphorus (Ackerson, 1985). Increasing both water and nitrogen at ambient CO_2 raised both the AM and PM starch levels in these leaves (C-N+W+, Fig. 35). The effect of increasing carbon dioxide along with either water (C+N-W+, Fig. 36) or nitrogen (C+N+W-, Fig. 37) raised both the AM and PM starch levels in these leaves more than the treatment in which additional water and nitrogen were supplied, but at ambient CO_2 (C-N+W+, Fig. 35). Increasing all three inputs (C+N+W+, Fig. 38) produced diurnal and seasonal starch patterns very similar to those from elevated CO_2 and water alone (C+N-W+, Fig. 36). In all of these treatments, it is clear that cotton leaf starch is highest during periods of lowest water stress. Also, the starch levels in these leaves exposed to elevated CO_2 greatly exceeded those in the neighboring plants sampled in the FIZZ/FACE experiment, as will be discussed later. These leaves often had PM starch contents which exceeded 40 gm^{-2}, but the corresponding FIZZ/FACE leaves had starch values which never exceeded half this value.

In cotton, the diurnal fluctuation in plant leaf starch (i.e., PM-AM content) represents the amount of carbon which is either respired or exported from the leaf to the rest of the plant during the night, a time of the day which is important for cotton plant growth (Radin, 1983) and flowering. Assuming that leaf respiration is constant across the various treatments, this starch difference would be therefore related to the carbon exported from these leaves during the night. During daylight hours, cotton leaf carbon export depends upon leaf sucrose content (Huber and Hendrix, 1986; Hendrix and Grange, 1988) and daylight export from cotton leaves is relatively constant across various environmental treatments. Night export rates, however, can vary with environment. The amount of starch in cotton leaves at the end of the light period is directly proportional to the carbon exported to the plant from that leaf during the following night up to a maximal export rate equal to the daytime rate (Hendrix and Grange, 1988). If starch in cotton leaves at the end of the light period is below a certain value, nighttime carbon export ceases and growth in such plants takes place only during daylight hours (Hendrix and Grange, 1988). Since night export from cotton leaves comes mainly from starch, leaves with very little starch would break it down completely during the following night and exhibit AM starch values approaching zero.

6. Stomatal densities

Stomatal densities and epidermal cell densities were measured on the adaxial (upper) and abaxial (lower) sides of a single fully expanded leaf from three plants in each chamber using the leaf impression technique of Sampson (1961), with the following modification. Leaf impressions were taken using a clear, fast drying acrylic liquid (Noxell Corp., Hunt Valley, MD). The leaf impressions were taken near the center of the leaf surfaces, but did not include any major veins. Stomatal counts were made in three randomly selected light microscope fields from each leaf. In one of the three fields the number of epidermal cells was also counted. Each field consisted of 0.25 mm^2 at 63X magnification. The leaf impressions were collected on 22 September 1987. In addition, a stomatal index (SI) was calculated from the stomatal and epidermal cell counts according to Woodward (1987), where SI = (stomatal density) / (stomatal density + epidermal cell density) X 100. A separate analysis of variance (ANOVA) was calculated for each of the three response variables.

A summary of the statistical significance from the ANOVAs is shown in Table 16 and mean responses are shown in Table 17. The CO_2 treatments had no significant effect on any of the three response variables. Nitrogen, however, did have a significant effect on the number of stomates and epidermal cells per unit leaf area, with fewer of each found in the high nitrogen treatment. There was a significant CO_2 by nitrogen effect on both stomates and epidermal cells per unit leaf area, with fewer stomates found in the high CO_2-high nitrogen treatment.

The dry irrigation treatment significantly increased epidermal cell density on both leaf surfaces, but did not affect stomatal density or stomatal index. The only other significant factor in the analysis was leaf surface. Both stomatal and epidermal cell densities were significantly higher on the abaxial (lower) leaf surface. The stomatal index was also higher on the abaxial leaf surface.

These results differ from those reported for the 1986 experiment, where CO_2 had a significant effect on stomatal density of both leaf surfaces, the dry treatment significantly increased stomatal density on the adaxial leaf surface, and nitrogen had no effect on stomatal density. One reason for the significant nitrogen effects in 1987 was that a greater difference in nitrogen levels was achieved (Table 11) than in the 1986 experiment. The reason for a lack of a significant stomatal density (averaged over both leaf surfaces) response to CO_2 is not clear. The difference in the ambient and 650 CO_2 treatments in 1987 was only 5.4%, compared with 10.0% in 1986. In both years, however, the trend indicated that stomatal density was greater in the high CO_2 treatment.

7. Leaf water potential, relative leaf water content, leaf dry matter content, and specific leaf weight.

The sampling procedures for the leaf water potential were similar to those in 1986. Briefly, two leaves per plot were sampled just before dawn and another two at noon 2 days and 6 days after weekly irrigations and brought into the laboratory. The weekly samplings alternated between Rep I and Rep II, so the season was divided into biweekly intervals for statistical analysis. To take the samples, a plastic Ziploc bag was humidified with a breath of air and placed over the youngest fully expanded leaf, usually the fourth or fifth from the shoot apex, and then the petiole was severed with a razor blade. The bag was sealed and stored under a wet towel in a Styrofoam chest for transport to the laboratory, where water potential measurements were made using a pressure bomb.

At the same sampling times (usually) as the water potential leaves were taken, four (usually) leaf disks (16.0 mm dia.) were punched from one side of the youngest fully-expanded leaf from each of two other plants and placed in a glass vial for transport to the laboratory for determination of relative leaf water content, dry matter content, and specific leaf weight. Predawn and noon samples were punched from separate halves of the same leaf on a particular sampling day.

Special care was taken to minimize adsorption and desorption of water on the walls of the vials and caps. The vials were left on a laboratory bench (caps off) for a least 12 hours before determining a tare weight and taking them to the field for sampling. After sampling, the vials plus disks were weighed for determination of fresh weight, W_f. Then the disks were floated on distilled water in covered petri dishes within a chamber at 30 C and dim light for 24 hours, while at the same time the vials and caps were dried in a convection oven at 70 C. Then the vials were tared again, the disks were blotted dry, and quickly weighed again in the vials to determine saturated weight, W_s. The final stage was to dry the disks overnight in the oven followed by weighing the vial plus dry matter, then emptying the contents and reweighing the vial to determine dry weight, W_d. The oven-dry vial weights were compared to be sure they were essentially the same. Relative leaf water content, RLWC (%), was computed from: $RLWC = 100 * (W_f-W_d)/(W_s-W_d)$. Dry matter contents, DMC (%), were computed from: $DMC = 100 * (W_d/W_f)$. Specific leaf weights, SLW (g/m^2), were computed from $W_d/(n * A)$, where n is the number of leaf disks (usually 8) and A is the area of each. All of the data were statistically analyzed using an analysis of variance with biweekly sampling intervals as repeated measure subsamples (Table 10, Kimball et al., 1986). Significant differences usually existed among the data from the different sampling intervals, but the data were averaged across them for presentation of the results in Tables 18 - 21.

The leaf water potential results are presented in Table 18. As expected, the deficit irrigation (dry) treatment again caused the leaves to be drier (more negative LWP), although the difference was statistically significant only for the noon, 6-day-after-irrigation data. The effect of the CO_2 treatment was opposite to that observed in past years. The near doubling of CO_2 concentration tended to make the leaves wetter (less negative LWP), but the only the noon, 6-day-after-irrigation difference was significant. There was a tendency for the N^- leaves to be drier than those of the N^+, but again only the noon, 6-day-after-irrigation difference was significant. For these latter data, the drying effect on leaf water potential by the nitrogen stress treatment (N^-) was significantly greater in the dry irrigation treatment.

The relative leaf water content (RLWC) results are presented in Table 19. The effect of the dry irrigation treatment was as expected, the leaves from the dry treatment being in fact drier, although the differences were statistically significant only for the predawn data.

There was a surprising lack of response to the CO_2 treatments, with really no differences at all for any of the sampling conditions. These results conflict with those from past years, which suggested that the leaves from the high CO_2 treatment were drier. There was no significant effect of the nitrogen treatment on RLWC. Considering that the LWP data (Table 18) indicated the nitrogen stress (N^-) leaves were drier, there probably was a shift in the LWP - RLWC ("PV") curve as observed previously by Radin and Parker (1979).

Thus, these 1987 LWP and RLWC data suggest that only the irrigation and nitrogen treatments had much effect on leaf water status, the dry and N^- treatment drying the leaves, as expected. The CO_2 treatments had very little impact, the latter result being somewhat surprising in view of results from past years when the leaves from the high CO_2 treatment tended to be drier.

The leaf dry matter contents (DMC) and specific leaf weights (SLW) are presented in Tables 20 and 21, respectively. Both sets of data showed very similar responses to the applied treatments. The nitrogen treatments had essentially no effect. The dry irrigation treatment tended to make the leaves slightly drier (Table 20) and heavier (per unit area, Table 21), but the differences were not statistically significant. On the other hand, the CO_2 treatment had a huge effect, significantly increasing both DMC and SLW for all sampling conditions. These large increases in leaf weight at high CO_2 were probably due to the higher accumulation of starch in the leaves at high CO_2, as discussed previously (Figures 31 - 38).

FIZZ/FACE EXPERIMENT

A. Materials and Methods

1. Overall design, plot plan, and culture of the experimental crop

This experiment involved the application of CO_2 to cotton in an open field, as was done previously in 1986. One method was to irrigate the cotton with carbonated (FIZZ) water, and the second was to release gaseous CO_2 from tubing at the base of the plants, a free-air CO_2 enrichment (FACE) experiment. The plot plan was the same as in 1986 (Figure 39). There were four replicates each of the control (C), FIZZ (Z), and FACE (A) plots. The basic plot areas were 5 rows (40 inch, 1.016 m spacing) wide by 5 m long. The control and fizz plots were planted in 8 row strips, so there were 2 border rows on one side and 1 on the other. The tubing for the A plots was laid along a 20 m length of 20 rows, thus forming a 7 m border as indicated by the dashed lines in Figure 39. Weather data were again recorded on a mast installed between the C and Z plots of Rep I.

2. FIZZ Irrigation and CO_2, Water, and Nitrogen Applications

The irrigation system was the same as used in 1986 (Figure 28, Kimball et al., 1986). Briefly, a drip irrigation system was used to apply the water. The capacity of the city water supply limited the area that could be irrigated to about 800 m^2. Accordingly, the field was divided into sections, which followed the FACE reps (Figure 39). In 1986 all the control plots were irrigated at the same time, as a separate block, as were the FIZZ plots also. Irrigating the control and FIZZ plots separately made it difficult to compare the time courses of soil CO_2 concentration. Therefore, in 1987 the control and FIZZ plots were irrigated at the same time, although the duration of the irrigation for each was adjusted to compensate for differences in flow rate.

The irrigation and rain amounts are presented in Table 22. The first irrigation was applied by flooding, estimated at 150 mm. The amount to apply each week was based on pan evaporation times LAI/3 (Equation 1), similar to the CO_2-WATER-NITROGEN experiment. However, for the FIZZ/FACE experiment, the water was applied over the 6 days of the week when the CO_2-WATER-NITROGEN experiment was not being irrigated. The control and FIZZ plots were irrigated generally starting about 08:00 on each day, followed sequentially by the 4 reps of the FACE plots.

CO_2 was injected into the irrigation water applied to FIZZ plots using a commercial carbonator (Carboflow, Inc.), as was done during 1986 (Kimball et al., 1986). The machine leaked badly early in the season and was repaired by the company, but from 17 June through 7 July the FIZZ plots received normal water. For a CO_2 flow rate of 34 liters/min (STP, 1.1 g/s) and a total FIZZ plot area of 369 m^2, the CO_2 release rate was 3.1 mg m^{-2} s^{-1}. Multiplying by the total CO_2 application time of 220.1 hr (Table 22), the total amount of CO_2 used in the FIZZ plots was 2.39 kg m^{-2}.

Nitrogen fertilizer was applied to the FIZZ/FACE experiment plots by injection into the drip irrigation system, as was done for the N^+ plots of the CO_2-WATER-NITROGEN experiment. The amounts applied are presented in Table 23. They should have been equal (on a unit area basis), but they were not, and these nitrogen differences may have confounded the experiment. The reason that the 4 reps of the FACE plots did not receive the same amount per unit area was that equal amounts per Rep were applied without accounting for the different areas, so that Rep II with an irrigated area of 650 m^2 received nearly twice as much (134 kg/ha compared to 85) on a per unit area basis than Rep IV with an irrigated area of 1195 m^2. The reason the FIZZ and Control plots did not receive the same amount was that the FIZZ carbonator increased the operating pressure and water flow rate to the FIZZ plots compared to the controls. The lengths of the irrigations were adjusted so that the FIZZ and control plots received the same amounts of irrigation water. However, because the nitrogen was injected for about a half hour period during one of the irrigations each week, the differing water flow rates to the FIZZ and control plots must have caused relatively more nitrogen to be applied to the FIZZ plots than to the controls. These application differences were realized too late in the season to do much effective compensation, so we have to conclude that the nitrogen fertilizer application amounts did differ among the plots, and that they may have affected the results. The fact that the control plots only received 88 kg/ha is particularly troublesome, because any positive responses to CO_2 in the FIZZ or FACE plots can not now be attributed with confidence to the CO_2 treatment, rather it could be a nitrogen fertilizer response.

3. FACE system design and CO_2 use

The free-air CO_2 enrichment (FACE) experiment was performed the same as in 1986 (Kimball et al., 1986), except that length of time per day that the CO_2 was released was reduced from 11 hours to 4 hours centered approximately on solar noon (10:30 - 14:30 MST). The CO_2 was again released through drip irrigation tubing laid along the rows at the base of the plants. The tubing was identical to but in addition to that used for irrigation. The emitters were spaced 0.3048 m apart and rated at 1 liter of water per hour. For this application they emitted about 0.1 liter/min of CO_2 (at 6 kPa).

The CO_2 was released at a rate of 120 liters/min per FACE plot or 10 mg m^{-2} s^{-1} for the 4 hours per day starting on 19 June and continuing 94 days until 21 September. Thus, the total amount of FACE CO_2 released was 13.5 kg/m^2, which is about 1/3 that used in 1986 but still about 6 times that used by the FIZZ plots.

4. Atmospheric CO_2 concentrations

Air sampling manifolds were mounted in every plot at 75% of plant height, as done previously (Kimball et al., 1986). Additional manifolds were mounted in Rep IV at the 25 and 50% plant heights and at 1.8 above the soil surface. The heights of the manifolds were adjusted weekly as the crop grew (except those at 1.8 m). Pumps were installed at the base of the manifolds in the field and continuously pumped sample air to the instrument cabin where a computer-controlled sampling system sequentially selected the air from the various field cites and directed it through an infrared CO_2 analyzer for analysis. Every 30 seconds the system cycled from one station to the next continually from the time of the start of the FACE experiment (19 June) until its end (21 September).

The CO_2 concentrations of the air in the various plots of the FIZZ/FACE experiment are presented in Tables 24 - 26 and Figures 40 - 44. The mean CO_2 concentrations at the 75% plant height are presented in Table 24. The mean daytime CO_2 concentration in the control plots was 342 while that of the FIZZ plots was essentially the same at 346 and that of the FACE plots was 377. Looking at the 09:00 to 10:00 data and remembering that the FIZZ irrigations started usually at 08:00 (6 days per week), there was a slight enrichment of the atmosphere by the FIZZ water from 347 to 360 $\mu\ell/\ell$. Similarly remembering that the FACE releases started at 10:30, the 12:00-13:00 data show a midday enrichment in the FACE plots to 449 $\mu\ell/\ell$, which is somewhat lower than for the same midday period in 1986. The diurnal course of the CO_2 concentrations for the 75% plant height in Rep I is illustrated in Figure 40.

Independent measurements of the CO_2 concentrations were obtained with a Li-Cor 6200 Portable Photosynthesis System on 9 days during the season during the course of taking leaf photosynthesis measurements. The means of these data are presented in Table 25, and they indicate that the level of enrichment near midday in the FACE plots was about 391 $\mu\ell/\ell$. This is lower than the 449 $\mu\ell/\ell$ discussed above that was measured by the automatic sampling system. However, the photosynthesis measurements were taken on leaves exposed to the direct sun at the top of the canopy, where the concentration would be expected to less than at 75% plant height, so these data appear reasonably consistent. One curious thing about the data in Table 25, however, is that the CO_2 concentrations for the first leaf were about 28 $\mu\ell/\ell$ higher than the second and 19 $\mu\ell/\ell$ higher than the third. We have no explanation as to why this should be in a open field. Thus some of the change in CO_2 concentration going from leaf 1 to 3 in the open-top chambers (Table 7) may be some artifact of the photosynthesis measurements, rather than a design problem with the CO_2 distribution system in the open-top chambers.

The mean CO_2 concentrations at the various heights for Rep IV are presented in Table 26. At 1.8 m there was an increase of 14 $\mu\ell/\ell$ in the FACE plot compared to the control plot from 12:00 to 13:00. Otherwise there was little difference among plots or sample averaging times at the 1.8 m height. Close to the base of the canopy at the 25% height, however, the concentration was 569 $\mu\ell/\ell$ (228 $\mu\ell/\ell$ above the control) at midday. Earlier in the morning from 09:00 to 10:00 the concentrations at the 25% plant height in the FIZZ plot reached 394 $\mu\ell/\ell$ which was 43 $\mu\ell/\ell$ above the control.

The diurnal course of the CO_2 concentrations at the various heights in Rep IV is shown in Figures 41, 42, and 43 for the control, FIZZ, and FACE plots, respectively. In Figure 41 for the control plot, the curves for the various heights fall almost on top of each other, except at night when the concentrations at the 1.8 m height were about 40 $\mu\ell/\ell$ lower than those within the plant canopy. In Figure 42 for the FIZZ plot, there was some increase in concentration within the crop canopy starting after 08:00, but it declined to the 1.8 m concentration by 15:00. There appeared to be higher atmospheric CO_2 concentrations in the FIZZ plots when fertilizer was being injected into the carbonated water, suggesting that perhaps the fertilizer was decreasing the CO_2 solubility. Figure 43 for the FACE plot illustrates that at midday during the hours of CO_2 release, there was a marked enrichment of the atmosphere within the crop canopy, but not much effect at 1.8 m. Figure 43 looks different than the corresponding figure from 1986 (Figure 36, Kimball et al., 1986) because the early morning release in 1986 under relatively calm conditions resulted in concentrations of over 1400 $\mu\ell/\ell$ at the 25% height. At midday the concentrations for 1987 were only about 20 $\mu\ell/\ell$ lower in 1987 than 1986.

Vertical profiles of CO_2 concentration are shown in Figure 44 for hours ending about 10:00 and 12:00. At 10:00 the FACE release had not started, but the FIZZ irrigation was underway, and the slight increase in CO_2 in the atmosphere of the FIZZ plots is apparent. At 12:00 the FACE release was underway, but the FIZZ irrigations had usually stopped. The large increase of CO_2 in the atmosphere in the FACE plots is readily apparent, while concentrations in the FIZZ plots had begun to decrease toward those in the ambient control plot. Extrapolating up to the top of the canopy from the 50 and 75% heights, the concentration at the top of the canopy probably was about 400 $\mu\ell/\ell$, which closely agrees with the mean 391 $\mu\ell/\ell$ recorded during photosynthesis measurements (Table 25), as discussed previously.

B. Results

1. Leaf Area, Flower Production, Boll Retention, Biomass, and Yield

Daily flower counts, boll load, and rate of boll retention were obtained from tagging of white blooms five days each week throughout the season. Blooms were tagged on five meters of row in each replication. Boll loading for the weekend was calculated from interpolation of the data on the adjacent Friday and Monday.

Intermediate harvests consisting of three plants each week were performed. The plants chosen for harvest were from a row which did not border the final-harvest row. They were removed each week from within a particular meter of row, proceeding systematically down the row to the next meter for the next week and so on. Counts were made on the harvested plants of the numbers of squares, flowers, bolls, and abscised sites. The plants were separated into stems, leaves, and bolls, and the dry weight of each were determined. Leaf area was also measured and leaf area index (LAI) and leaf area per active boll (LA/B) were computed.

Final harvest data was obtained from all the plants in the five meters which were tagged for boll load. Plots were harvested from 29 September to 10 October 1987. Green bolls at the time of harvest were given a final estimated weight for inclusion in the totals for each plot. The final weight of these bolls was assumed to be 80% of the average weight of open bolls for the plot. The data shown are averages of four replications.

The final yields of the FIZZ/FACE experiment plots are presented in Table 27. There was a substantial effect of the FIZZ and FACE treatments resulting in seed cotton increases of 21 and 22%, respectively. The yield increase of 22% for the FACE is about the same as in 1986, which is especially interesting considering that the additional CO_2 was supplied for 11 hours per day in 1986 and only 4 hours per day in 1987. Using a figure of 450 $\mu\ell/\ell$ for the midday CO_2 concentration (Table 24), a yield increase of 22% is exactly what one would predict from the regression line in Figure 17 based on all the open-top chamber experiments.

However, the question raised about differing nitrogen fertilizer applications among the various plots (Table 23) needs to be addressed. Therefore, the final biomass and seed cotton yields (Table 27) were plotted against the amount of applied nitrogen for the FACE plots (Figure 45). There appears to be no positive effect of the varying nitrogen on either yield or biomass among the individual FACE plots. Moreover, the range in nitrogen application among the FACE plots spans the control and FIZZ rates. Therefore, assuming no large interactions between CO_2 and nitrogen, we have some assurance that at these levels of nitrogen applications, the differences among them were not significant, and our efforts have not been in vain.

The boll loading, flower production rates, and boll retention through the season are shown in Figures 46, 47, and 48. Examination of the boll loading of both the FACE and FIZZ treatments (Figure 46) shows that the time period day 190 to 210 was the time of divergence of the treatments. These dates also coincide with the divergence observed in the open-topped chambers. It may be that by confining the release to this portion of the season, the volume of CO_2 released could be reduced substantially without greatly influencing the yield enhancement effect. The additional boll load of the FACE and FIZZ treatments was achieved by both greater numbers of flowers (Figure 47) and by higher boll retention during the period day 190 to 210 (Figure 48).

The leaf area index and leaf area per boll through the season are presented in Table 28. The carbonated water (FIZZ) treatment had greater leaf area during early boll setting and throughout the season. The effect of FACE treatment was to increase leaf area slightly and reduce the LA/B somewhat. This would indicate that the higher photosynthetic rate of the leaves was effective in inducing a greater boll carrying capacity of the canopy.

2. Elemental analysis

An elemental analysis was performed on leaf blades sampled on 23 July (DOY 204) from Rep II by a commercial laboratory, and the results are presented in Table 29. The nitrogen, N, values suggest that only the FIZZ plots had adequate nitrogen, yet Rep II of the FACE plots received just as much fertilizer nitrogen (per unit area) as did the FIZZ plots (Table 23). The only other element which appeared to be deficient was zinc, Zn, which was low in all treatments, but more so in the FACE plot. No visual zinc deficiency symptoms were observed, so whether adding zinc to the soil or plants in the field would really promote better growth is a question that needs to be addressed with another experiment.

3. Photosynthesis and Stomatal Conductance

Net photosynthesis and stomatal conductance measurements were taken in the FIZZ/FACE experiment using a Li-Cor 6200 Portable Photosynthesis System. The procedure was similar to that already described for the CO_2-WATER-NITROGEN experiment in that the measurements were taken near midday on 3 leaves per plot choosing the youngest fully-expanded leaves for measurement. The measurements were taken weekly under clear sky, usually on Wednesday depending on sky conditions.

The net photosynthesis results are presented in Figure 49 and Table 30. Unlike 1986, there was no apparent decline in photosynthetic rates through the course of the season. The mean rate of 30.4 $\mu mol\ m^{-2}\ s^{-1}$ in the FACE plots was a significant (0.05) 15% higher than those in the control (26.5 $\mu mol\ m^{-2}\ s^{-1}$) and FIZZ plots, which were no different.

The stomatal conductance results are presented in Figure 50 and Table 30. As already mentioned, a temperature sensor in the instrument invalidated the June conductance data, so there were fewer conductance than photosynthesis data. For most days the "raw" conductance values computed by the instrument averaged about 2 cm/s, but on some days they were considerably higher for no apparent reason, so day-of-year was a significant factor in the analysis. However, the CO_2 treatment had no significant effect on these "raw" conductance values, which averaged 2.9 cm/s for the season.

These "raw" stomatal conductance values were also "adjusted" for the leaf chamber effect as recommended by Idso et al. (1987) and as described previously for the CO_2-WATER-NITROGEN experiment. The adjustment had the effect of increasing the mean values from about 3 to about 8 cm/s. Considerably more scatter and instability were also introduced into these data (Figure 50). Even though the mean adjusted conductance of the FACE plot was higher and that of the FIZZ was lower than that of the controls, (Table 30), these differences were not significant. It remains to be seen whether the 3 or the 8 cm/s is the more accurate value; in the latter event it would be desirable to have a more stable adjustment procedure.

4. Leaf starch content

Leaves were sampled from the FIZZ/FACE plots and analyzed for starch content using sampling and analysis procedures described previously for the CO_2/WATER/NITROGEN experiment, except that sampling was done only once per week on these daily irrigated plots.

Free air CO_2 enrichment (FACE) appeared to have a stimulatory effect on cotton leaf starch, particularly at the end of the growing season (Figs. 51, 52). It had a very pronounced effect upon the number of active bolls (i.e., the number of bolls $\leq$ 40 days old) and upon the number of flowers (Figs. 51, 52). Fizz water irrigation (Fig. 53) did not appear to have a significant effect upon leaf starch content but it did increase the peak number of flowers and the number of active bolls. The difference between the AM (daily minimum) and PM (daily maximum) leaf starch content was relatively constant for all three treatments (Controls, FACE and FIZZ) during the first half of the growing season. Both AM and PM leaf starch content values decreased with time during this period but in such a way that their difference was relatively constant. At Julian date 210, however, the difference between the AM and PM starch content collapsed. This occurred by a <u>rise</u> in the AM starch content as well as a decrease in the PM content. This cessation in diurnal starch content fluctuation occurred <u>after</u> the peak in the number of active bolls carried by the plants. Further, simultaneous sampling in the open-top chambers (CO_2/WATER/NITROGEN experiment described previously), where cutout did not occur, showed that this diurnal starch fluctuation collapse only occurred in plots where cutout occurred. In all three FIZZ/FACE treatments, this diurnal starch fluctuation cutout lasted for twenty days and disappeared when flowering resumed.

We proposed earlier (Hendrix and Grange, 1988) that diurnal starch change is related to the amount of carbon exported from cotton leaves during the night. Laboratory experiments showed that if the PM leaf starch content is $\geq$ 3 $g.m^{-2}$, nocturnal leaf carbon export will continue at rates comparable to those observed during daylight hours and for PM starch contents less than this value, the nocturnal carbon export of cotton leaves was directly proportional to the leaf PM starch content. These laboratory data suggest that PM leaf starch content is the driving force for nocturnal leaf carbon export. It is difficult to imagine, therefore, how leaf starch content could be driving nocturnal leaf carbon export during this 20 day starch cutout. Perhaps a shift occurs during this period to carbon export from some other pool, such as stem or root starch. Another interesting aspect of this collapse is that it occurs when the number of active bolls per meter is decreasing. During the 20 day starch cutout, cotton plants may not be storing or calling upon starch reserves in their leaves, but may be calling upon other pools within the plant. This carbohydrate pool shift depends upon cutout but is apparently unaffected by CO_2.

MODELING OF PLANT GROWTH

The bulk of the 1987 plant growth modeling effort consisted of preparing the Phoenix open-top chamber and open-field data sets (Kimball et al., 1983, 1984, 1985, 1986) on cotton for the years 1983-1987 into the proper format for comparison with predictions of growth using the cotton growth model called GOSSYM (Baker et al., 1983). This exercise also included editing the data to remove known bad values and to fill some gaps from the record using comparable data from other USWCL experiments, from the National Weather Service, or from Arizona State University.

Many comparisons were made between GOSSYM (September 1986 version) predictions and open-field, ambient-CO_2 data with poor agreement. The left side of Figure 54 illustrates the lack of agreement for one data set from Rep I, 1983. Upon notice of this, Mississippi State personnel furnished an updated July 1987 version of GOSSYM, which was able to simulate the growth in the ambient CO_2 plots much better than the previous version, as illustrated on the right side of Figure 54 for the Rep I, 1983 data.

Once respectable agreement between predictions and observations was obtained for open-field, ambient-CO_2 conditions, the photosynthesis equation in July 1987 GOSSYM was manipulated to incorporate the effects of elevated CO_2. The relative increase in net photosynthesis due to CO_2 as reported by 12 sources was plotted, and a linear equation was fitted by eye to the data (Figure 55). The equation predicts a 50% increase in net photosynthesis for a 300 ppm increase in CO_2 concentration from 350 to 650 ppm. Of course, the equation should not be used much above 650 ppm. CO_2 concentration was then made an input variable to GOSSYM, and the "relative" equation in Figure 55 was attached as a multiplier to the "absolute" photosynthesis equation in GOSSYM. Considering the degree of scatter in Figure 55, initial comparisons between predictions and data from the CO_2-enriched open-top chambers showed surprisingly good agreement, as illustrated by Figure 56 for the Rep I, 1983 data.

BEET ARMYWORM GROWTH AND DEVELOPMENT ON CO_2-ENRICHED COTTON

The enhanced carbohydrate under CO_2 enrichment decreases nitrogen : carbon ratios in some plant tissues (Oechel & Strain 1985). This tends to decrease the nutritive quality of those tissues. Such CO_2 related changes may alter the damage done by herbivorous insects.

To date, published studies of insect development on CO_2-enriched plants have been conducted on two leaf-feeding caterpillars: the soybean looper, *Pseudoplusia includens* (Walker), on soybeans and the cabbage looper, *Trichoplusia ni* (Hubner), on lima beans (Lincoln et al. 1986, Osbrink et al. 1987). In general, these studies showed that these leaf-feeding caterpillars did not do as well on CO_2-enriched plants as they did on the ambient-CO_2-control plants. Since similar developmental data have not been gathered on leaf-feeding caterpillars on cotton, a study was initiated on the growth, developmental time, and survival of the beet armyworm (BAW), *Spodoptera exigua* (Hubner) reared on CO_2-enriched cotton.

A. Materials and Methods

Deltapine 61 cotton seedlings were grown in two greenhouses (30°C day, 24°C night). One greenhouse was maintained at a CO_2 level of 650 ppm and the other at an ambient CO_2 level of 325 ppm. Hoagland solution was used to fertilize the seedlings after the first 2 true leaves appeared. Two fertilizer levels were used: low, a 75-ml treatment applied once; and high, 75-ml treatments applied every other day.

The tests were conducted in 4 incubators held at 30°C with an 18:6 light:dark photoperiod. Air was piped from the CO_2-enriched greenhouse to 2 of the incubators and from the ambient greenhouse to the other 2 incubators. Eight seedlings were kept in each incubator. One - 3 newborn BAW larvae were placed on each cotton seedling (at first 2 true leaves). Containment was accomplished using clear plastic cages (with some mesh-covered ventilation holes) that enclosed each seedling from the stem upward. Seedlings were replaced as needed as the growing larvae defoliated them. BAW were collected when mature larvae entered the "wandering" (prepupal) stage or pupated. Pupae were weighed and sexed. Data were summarized and analyzed by analysis of variance to determine BAW growth, developmental time, and survival.

B. Results

BAW reared on CO_2-enriched cotton seedlings weighed significantly less (87.8 mg) than controls (96.8 mg) (Table 31). The growth of female BAW reared on CO_2-enriched seedlings on the high fertilizer level was most affected (87.3 mg versus 101.0 for controls, Table 32). A developmental time of 14.6 days was a significant 2-day increase for BAW reared on CO_2-enriched seedlings compared to the control group (Table 33). As with growth, the development of female BAW reared on CO_2-enriched seedlings on the high fertilizer level was most affected (14.2 versus 12.4 days, Table 34). The significant difference between the survival rate of 19.1% for BAW reared on CO_2-enriched seedlings on the high fertilizer level compared to the 41.6% survival rate of the controls was striking (Table 35); more females survived than males by a significant 2:1 ratio (Table 36).

The results presented here support the concept that the foliage of CO_2-enriched plants does not meet the needs of insect herbivores as well as foliage from plants grown at present ambient levels of CO_2. The significant decrease in survival should be investigated at more temperatures to determine relationships between CO_2 enrichment, survival, and temperature. If further work confirms that survival is significantly affected across a range of temperatures, then survival, as a CO_2-dependent parameter, can certainly be expected to alter the population dynamics of BAW. Also, the dominant effect of fertilizer levels on BAW development in the present work demonstrates the importance of this parameter to future work. Additional studies will be needed to assess the overall effect of CO_2-enriched plants on insect populations.

SUMMARY AND CONCLUSIONS

The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during the next century. To determine what effects this CO_2 increase is likely to have on the productivity, water relations, and physiological processes of field-grown cotton (as well as few other species), the USDA-ARS U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory conducted CO_2 enrichment experiments on field-grown cotton and other plants during 1987, and this report presents the results of those experiments.

In the largest experiment, called the CO_2/WATER/NITROGEN experiment, the effects of the three-way interaction between CO_2 concentration, water availability, and nitrogen fertility on the growth of cotton were investigated. This was the second year of a planned 2-year experiment initiated in 1986. Using open-top chambers, CO_2 concentrations of ambient (340 $\mu\ell/\ell$) and 640 $\mu\ell/\ell$ were maintained. There was a well-watered treatment (wet) and a water stress treatment (dry) that received 2/3 as much water. Half the plots received 230 kg/ha of nitrogen in the irrigation water (N+), while the others received no added fertilizer nitrogen (N-). The N- treatment was severe in 1987 because (1) the experiment plots were placed on the same land as 1986, and (2) a winter crop of barley was grown on the land between the 1986 and 1987, which was cut while still green and removed. Significant findings from this experiment included the following:

1. The N- treatment significantly lowered petiole nitrate levels and reduced seed cotton (lint + seed) yields an average 29%. However, even at the low N fertility level, CO_2 enrichment substantially increased yields, averaging 52 and 37% for the dry and wet treatments, respectively.

2. The response to the near-doubling of CO_2 concentration was greater under water-stress conditions, consistent with most prior observations. With added nitrogen, CO_2 enrichment increased yields 43% in the dry treatment compared to 25% in the wet. At low N the figures were 52 and 37%, as noted above. The average 25% increase with CO_2 enrichment under high N, well-watered conditions is lower than observed in these experiments before, a result of inconsistent growth in 2 plots.

3. There was a decrease in harvest index with CO_2 enrichment in 1987, a change which did not occur in prior experiments.

4. Greater flower production rather than a higher retention of bolls was the yield component that contributed most to the greater produc-

tivity at high CO_2. The boll loading pattern was cyclic in all treatments, and the degree of CO_2 effect was influenced by the stage of the season.

5. Aggregating all the cotton yield data from similar CO_2-enrichment experiments from 1983-1987, a near-doubling of CO_2 concentration from 350 to 650 $\mu\ell/\ell$ increased cotton yields an overall average 64%. With adequate N, the yield increase has averaged 56 and 74% under well-watered and water-stress conditions, respectively. At low N, the increases have averaged 54 and 52% under the wet and dry conditions, respectively.

6. CO_2 enrichment increased leaf net photosynthesis by 45% when sampled 2 days after irrigations, and by 54% when sampled 6 days after irrigations. Neither the nitrogen nor the irrigation treatments significantly affected net photosynthesis.

7. CO_2 enrichment decreased stomatal conductance by 20% when sampled 2 days after irrigations, and by 17% when sampled 6 days after irrigations. The nitrogen treatments had no significant effect on stomatal conductance, nor did the irrigation treatments when sampled 2 days afterward. When sampled 6 days after irrigation, mean conductance was 33% lower for the dry treatment, as expected, but the difference was not statistically significant. When a recently recommended adjustment to correct for rapid stomatal closure during the measurements was applied, the conductance values were roughly doubled, but it had no effect on the relative differences among treatments.

8. The foliage temperature of non-water-stressed cotton was again shown to increase about 1.0 C with an increase in CO_2 concentration from 350 to 650 $\mu\ell/\ell$.

9. Cotton canopy net photosynthesis was increased 51% by CO_2 enrichment on 4 September days in the wet-N+ plots, as measured using "chimney-tops" mounted over the normally open-top chambers. The additional leaf layers that gave leaf area indices from 1.93 - 2.99 apparently compensated for the effects of mutual shading, leaf aging, and any difference in respiration, because the canopy net photosynthetic rates were close to the rates of individual young fully-expanded leaves at the top of the canopies, for the respective CO_2 levels.

10. Starch content of the leaves was significantly increased by CO_2 enrichment. However, when both water and nitrogen were low, dawn and dusk starch contents were close to the same, suggesting that under these stress conditions, the extra carbohydrate was not being transported out of the leaves to the rest of the plant. The starch contents also were higher under well-watered conditions at both low and high CO_2 and N.

11. Stomatal densities were increased significantly by the low nitrogen treatment, whereas water-stress increased epidermal cell density. CO_2 enrichment increased the mean stomatal density by +6%, a difference which was not statistically significant but which was consistent with the trend in 1986 when a +10% increase was observed.

12. Neither leaf water potentials nor relative leaf water contents were much affected by CO_2 enrichment, but as expected, the dry irrigation and N^- treatments resulted in drier leaves. The lack of a response to CO_2 is inconsistent with the results of 1986, when the CO_2 enriched leaves tended to be drier.

13. Leaf dry matter contents and specific leaf weights were little affected by the nitrogen or irrigation treatments, but CO_2 enrichment increased both significantly.

Another experiment, called the FIZZ/FACE experiment, was repeated for the second time in 1987 where the effects of CO_2 on cotton growing in an open field (no chambers) was observed. The CO_2 was applied using two methods - (1) irrigating with carbonated water (FIZZ) and (2) releasing CO_2 at the soil surface, a free-air CO_2 enrichment (FACE) experiment. The entire field was irrigated 6 days a week with the same ample amount of water from drip irrigation tubing, the water for the FIZZ treatment being supersaturated with CO_2 from a commercial carbonator first. The CO_2 to the FACE plots was distributed through a second set of drip irrigation tubing at a release rate of 10 mg m^{-2} s^{-1} from 10:30 - 14:30 daily, which resulted in an average midday CO_2 concentration at 75% of plant height of 449 $\mu\ell/\ell$. Enrichment for four hours per day was a departure from the methods of 1986 when the CO_2 was released 11 hours per day. Both treatments started near the end of June when the canopy was near full development and continued until harvest near the end of September. Control plots received normal irrigation and no free-air CO_2. There were 4 replications. Significant findings from the FIZZ/FACE experiment included the following:

1. Seed cotton yields were increased 21 and 22% by the FIZZ and FACE treatments, respectively. The former value is higher than 1986, while the latter is the same as 1986 (in spite of 7 hours per day less enrichment).

2. Net leaf photosynthesis was significantly increased 15% at midday by the FACE treatment, but there was no detectable effect of the FIZZ treatment. Neither treatment affected stomatal conductance.

3. Starch content of the leaves was increased by the FACE treatment in early July and near the end of the season, but there was no effect of the FIZZ treatment.

In a third experiment, the impact of elevated-CO_2-grown host cotton plants on the growth, development and survival of beet armyworms (BAW) [Spodoptera exigua (Hubner)] was investigated. Cotton seedlings were grown in two greenhouses at high and low levels of fertilizer in nutrient solution. One greenhouse was enriched to 650 $\mu\ell/\ell$ of CO_2 while the other was at ambient which averaged 325 $\mu\ell/\ell$. As the experiment progressed, seedlings were removed from the greenhouses and placed in lighted incubators which received the same CO_2 treatments as the greenhouses. Newborn BAW larvae were placed on the seedlings and allowed to eat and grow to maturity. Pupae were weighed and sexed. Significant findings include the following:

1. BAW reared on CO_2-enriched cotton seedlings weighed significantly less than the controls, with females at the high fertilizer level being most affected.

2. Development time of the BAW reared on the CO_2-enriched cotton was increased significantly, with females at the high fertilizer level being most affected.

3. The survival rate of BAW raised on the CO_2-enriched cotton was about half that of the controls.

Thus, it appears that CO_2-enriched cotton is of lower nutritive value to the beet armyworms, which implies they will have a more difficult time surviving in a future high-CO_2 world.

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Table 1. Irrigation and rain amounts for the CO_2-WATER-NITROGEN 1987 experiment.

DATE	DAY of YEAR	IRRIG (I) or RAIN (R)	WET PLOTS N+	WET PLOTS N-	DRY PLOTS N+	DRY PLOTS N-
			- - - - - - - - -	- -mm-	- - - - - -	- - -
16-Apr	106	I	144.0	89.0	136.9	115.0
23-Apr	113	I	18.4	11.8	17.3	14.6
30-Apr	120	R	0.3	0.3	0.3	0.3
30-Apr	120	I	21.5	13.8	19.5	17.0
05-May	125	I	15.6	10.0	16.1	12.6
08-May	128	I	43.9	28.1	40.7	36.2
11-May	131	R	1.5	1.5	1.5	1.5
15-May	135	R	0.3	0.3	0.3	0.3
26-May	146	I	8.0	8.3	6.6	6.1
02-Jun	153	I	11.7	13.3	7.6	9.9
06-Jun	157	R	1.8	1.8	1.8	1.8
09-Jun	160	I	36.6	34.7	21.9	20.4
16-Jun	167	I	44.3	70.1	34.9	45.7
18-Jun	169	I	40.0			
19-Jun	170	I	79.1			
23-Jun	174	I	42.0	73.6	27.3	34.9
30-Jun	181	I	60.2	23.2	38.1	18.1
07-Jul	188	I	50.3	67.6	39.3	37.6
14-Jul	195	I	78.5	68.6	50.5	51.9
21-Jul	202	I	62.1	69.3	46.7	40.1
27-Jul	208	R	11.9	11.9	11.9	11.9
28-Jul	209	R	1.3	1.3	1.3	1.3
28-Jul	209	I	59.4	57.1	31.4	35.9
01-Aug	213	R	18.0	18.0	18.0	18.0
04-Aug	216	I	41.1	44.8	20.1	21.8
05-Aug	217	R	12.7	12.7	12.7	12.7
11-Aug	223	I	45.4	41.5	48.6	23.2
11-Aug	223	R	7.9	7.9	7.9	7.9
18-Aug	230	I	72.5	68.0	32.3	47.6
23-Aug	235	R	3.6	3.6	3.6	3.6
24-Aug	236	R	3.0	3.0	3.0	3.0
25-Aug	237	I	47.5	54.8	10.1	23.6
25-Aug	237	R	21.1	21.1	21.1	21.1
01-Sep	244	I	65.7	61.8	55.4	43.9
08-Sep	251	I	83.0	83.5	46.2	49.8
15-Sep	258	I	61.0	58.6	43.4	44.3
22-Sep	265	I	58.5	59.9	35.7	37.5
23-Sep	266	R	9.7	9.7	9.7	9.7
24-Sep	267	R	6.9	6.9	6.9	6.9
30-Sep	273	I	69.2	65.4	40.1	39.9
		TOTALS	1459.5	1276.8	966.7	927.4

Table 2. Insecticide treatments applied during the 1987 CO_2/WATER-/NITROGEN experiment. Rates were those recommended by label.

Date	Insecticide
12 May	Malathion
27 May	"
21 June	"
11 July	"
17 July	"
12 August	Pydrin
13 August	Pydrin in open-top CO_2 chambers
14 August	Pydrin
15 August	Pydrin in FIZZ/FACE field release
19 August	Malathion & Pydrin
22 August	Malathion
2 Sept.	"
5 Sept.	"
9 Sept.	"
12 Sept.	"
15 Sept.	"
24 Sept.	"
28 Sept.	"
2 Oct.	"
5 Oct.	"
9 Oct.	"
13 Oct.	"

Table 3. Total water use during the 1987 CO_2-WATER-NITROGEN experiment as determined by the total amount of water applied through the drip irrigation system and adjusted for changes in soil moisture storage measured with neutron apparatus.

	TREATMENT							
	No Added N				Added N			
	Ambient		650		Ambient		650	
Item	Rep I	Rep II	Rep I	Rep II	Rep I	Rep II	Rep I	Rep II
WET PLOTS:								
16 Apr. soil water content	454	193	505	213	459	235	440	196
9 Oct. soil water content	422	185	456	217	382	240	408	199
Soil water content change	+32	+8	+49	-4	+77	-5	+32	-3
Irrigation + rain	1277	1277	1277	1277	1460	1460	1460	1460
Water use	1309	1285	1326	1273	1537	1455	1492	1457
average water use	1297		1300		1496		1475	
relative water use	1.000		1.002		1.000		0.986	
DRY PLOTS:								
16 Apr. soil water content	369	304	345	262	398	254	385	301
9 Oct. soil water content	263	231	316	218	267	191	263	194
Soil water content change	+106	+73	+29	+44	+131	+63	+122	+107
Irrigation + rain	927	927	927	927	967	967	967	967
Water use	1033	1000	956	971	1098	1030	1089	1074
average water use	1017		964		1064		1081	
relative water use	1.000		0.948		1.000		1.016	

Table 4. Nitrogen applications to the N^+ plots of the CO_2-WATER-NITROGEN 1987 experiment. At first the fertilizer source was urea, and then it was uran-32 starting on 14 July.

Date	Day of Year	Nitrogen Form NH_4^+	NO_3^-
		kg N/ha	
2 Jan	153	6.56	-
9 Jun	160	6.56	-
16 Jun	167	6.56	-
23 Jun	174	13.12	-
30 Jun	181	13.12	-
7 Jul	188	13.12	-
14 Jul	195	14.46	4.62
21 Jul	202	14.46	4.62
28 Jul	209	14.46	4.62
4 Aug	216	14.46	4.62
11 Aug	223	14.46	4.62
18 Aug	230	28.92	9.24
25 Aug	237	14.46	4.62
1 Sep	244	14.46	4.62
Totals		189.17	41.59
Total both forms			230.76

Table 5. Nitrate nitrogen and total nitrogen contents of the soil in the plots of the 1987 CO_2-WATER-NITROGEN experiment sampled at the start of the season (before) and again at the end (after). To convert to units of kg/ha, bulk densities of 1.45, 1.50, and 1.48 mg/m³ were used for the 0-15, 15-30, and 30-60 cm depth increments.

		NO_3^- - N					Total - N				
Plot	Depth	Before	After	Before	After	Decrease	Before	After	Before	After	Decrease
	cm	mg/kg		kg/ha			g/kg		kg/ha		
Ambient, dry, N^-, Rep I											
ID3	0-15	8.6	5.0	18.7	10.9	7.8	2.6	2.0	5700	4400	1300
	15-30	6.1	4.8	13.3	10.8	2.5	1.3	0.8	2900	1800	1100
	30-60	3.4	1.4	7.5	6.2	4.3	0.8	0.5	3600	2200	1300
		Totals		39.5	27.9	14.6			12200	8400	3700
Ambient, dry, N^-, Rep II											
IID1	0-15	5.4	4.1	11.7	8.9	2.8	2.1	1.9	4600	4100	400
	15-30	3.8	5.0	8.4	11.3	-2.9	1.3	1.4	2900	3200	-200
	30-60	2.9	2.3	6.3	10.2	-3.9	0.7	0.8	3100	3600	-400
		Totals		26.4	30.4	-4.0			10600	10900	-200
Ambient, dry, N^+, Rep I											
ID4	0-15	5.2	4.1	11.3	8.9	2.4	2.3	2.2	5000	4800	200
	15-30	5.6	6.1	12.2	13.7	-1.5	1.1	1.8	2500	4100	-1600
	30-60	5.4	3.8	11.7	16.9	-4.3	0.6	0.8	10200	12500	-900
		Totals		35.2	39.5	-4.3			10200	12500	-2300
Ambient, dry, N^+, Rep II											
IID2	0-15	2.7	4.1	5.9	8.9	-3.0	2.3	2.6	5000	5700	-700
	15-30	2.9	4.8	6.3	10.8	-4.5	1.1	0.8	2500	1800	700
	30-60	2.0	2.5	4.5	11.1	-6.6	0.6	0.6	2700	2700	0
		Totals		16.7	30.8	-14.1			10200	10200	0

Table 5. Nitrate nitrogen and total nitrogen contents of the soil in the plots of the 1987 CO_2-WATER-NITROGEN experiment sampled at the start of the season (before) and again at the end (after). To convert to units of kg/ha, bulk densities of 1.45, 1.50, and 1.48 mg/m³ were used for the 0-15, 15-30, and 30-60 cm depth increments. (continued)

		NO_3^- - N					Total - N				
Plot	Depth	Before	After	Before	After	Decrease	Before	After	Before	After	Decrease
	cm	------mg/kg------		----------kg/ha----------			------g/kg------		----------kg/ha----------		
Ambient, wet, N⁻, Rep I											
IH2	0-15	2.7	3.2	5.9	5.9	-1.1	1.7	1.9	3700	4100	-400
	15-30	4.1	2.0	8.8	4.5	4.3	1.5	1.7	3400	3800	-500
	30-60	3.2	2.3	7.0	10.2	-3.2	0.7	0.8	3100	3600	-400
		Totals		21.7	21.7	0			10200	11500	-1300
Ambient, wet, N⁻, Rep II											
IIH4	0-15	1.1	1.6	2.5	3.5	-1.0	1.7	1.9	3700	4100	-400
	15-30	1.4	0.9	2.9	2.0	0.9	1.4	1.4	3200	3200	0
	30-60	1.8	2.5	3.8	11.1	-7.3	0.8	0.8	3600	3600	0
		Totals		9.2	16.6	-7.4			10500	10900	-400
Ambient, wet, N⁺, Rep I											
IW3	0-15	2.7	3.6	5.9	7.8	-1.9	1.7	1.8	3700	3900	-200
	15-30	3.2	2.0	7.0	4.5	2.5	1.4	1.6	3200	3600	-500
	30-60	1.8	2.5	3.8	11.1	-6.7	0.6	0.8	2700	3600	-900
		Totals		16.7	23.4	-6.7			9600	11100	-1600
Ambient, wet, N⁺, Rep II											
IIH3	0-15	1.8	2.0	3.8	4.4	-0.6	1.7	2.0	3700	4400	-700
	15-30	1.8	0.9	3.8	2.0	1.8	1.4	1.6	3200	3600	-500
	30-60	2.3	1.8	5.0	8.0	-3.0	0.7	0.8	3100	3600	-400
		Totals		12.6	14.4	-1.8			10000	11600	-1600

Table 5. Nitrate nitrogen and total nitrogen contents of the soil in the plots of the 1987 CO_2-WATER-NITROGEN experiment sampled at the start of the season (before) and again at the end (after). To convert to units of kg/ha, bulk densities of 1.45, 1.50, and 1.48 mg/m^3 were used for the 0-15, 15-30, and 30-60 cm depth increments. (continued)

		NO_3^- - N					Total - N				
Plot	Depth	Before	After	Before	After	Decrease	Before	After	Before	After	Decrease
	cm	-----mg/kg-----		----------kg/ha----------			------g/kg-----		-----------kg/ha-----------		
650, dry, N^-, Rep I											
ID1	0-15	1.8	1.4	3.8	3.0	0.8	1.8	2.2	3900	4800	-900
	15-30	3.4	2.3	7.5	5.2	2.3	0.9	1.5	2000	3400	-1400
	30-60	3.2	1.8	6.8	8.0	-1.2	0.3	0.9	1300	4000	-2700
		Totals		18.1	16.2	1.9			7200	12200	-5000
650, dry, N^-, Rep II											
IID3	0-15	2.3	3.4	5.0	7.4	-2.4	1.8	2.2	3900	4800	-900
	15-30	2.7	3.4	5.9	7.7	-1.8	0.8	1.8	1800	4100	-2300
	30-60	2.9	2.0	6.3	8.9	-2.6	0.3	0.9	1300	4000	-2700
		Totals		17.2	24.0	-6.8			7000	12900	-5900
650, dry, N^+, Rep I											
ID2	0-15	7.9	3.2	17.2	7.0	10.2	2.8	2.1	6100	4600	1500
	15-30	6.1	7.0	13.1	5.8	7.3	1.0	0.9	2300	2000	200
	30-60	2.7	2.0	5.9	8.9	-3.0	0.5	0.7	2200	3100	-900
		Totals		36.2	21.7	14.5			10600	9700	800
650, dry, N^+, Rep II											
IID4	0-15	4.1	4.8	8.8	10.4	-1.6	2.0	2.1	4400	4600	-200
	15-30	4.3	3.6	9.3	8.1	1.2	1.6	1.4	3600	3200	500
	30-60	3.2	1.8	6.8	8.0	-1.2	0.7	0.9	3100	4000	-900
		Totals		24.9	26.5	-1.6			11100	11800	-600

Table 5. Nitrate nitrogen and total nitrogen contents of the soil in the plots of the 1987 CO_2-WATER-NITROGEN experiment sampled at the start of the season (before) and again at the end (after). To convert to units of kg/ha, bulk densities of 1.45, 1.50, and 1.48 mg/m^3 were used for the 0-15, 15-30, and 30-60 cm depth increments. (continued)

Plot	Depth	NO_3^- - N Before	NO_3^- - N After	NO_3^- - N Before	NO_3^- - N After	NO_3^- - N Decrease	Total - N Before	Total - N After	Total - N Before	Total - N After	Total - N Decrease
	cm	mg/kg	mg/kg	kg/ha	kg/ha	kg/ha	g/kg	g/kg	kg/ha	kg/ha	kg/ha
650, wet, N^-, Rep I											
IW4	0-15	1.4	2.3	2.9	5.0	-2.1	1.7	1.9	3700	4100	-400
	15-30	2.0	1.8	4.5	4.1	0.4	1.4	1.6	3200	3600	-500
	30-60	2.0	2.7	4.5	12.0	-7.5	0.6	0.7	2700	3100	-400
		Totals		11.9	21.1	-9.2			9600	10800	-1300
650, wet, N^-, Rep II											
IIW1	0-15	1.8	2.5	3.8	5.4	-1.6	1.7	2.0	3700	4400	-700
	15-30	1.8	1.4	3.8	3.2	0.6	1.4	1.7	3200	3800	-700
	30-60	1.4	2.0	2.9	8.9	-6.0	0.7	0.8	3100	3600	-400
		Totals		10.5	17.5	-7.0			10000	11800	-1800
650, wet, N^+, Rep I											
IW1	0-15	2.0	2.5	4.5	5.4	-0.9	1.8	2.1	3900	4600	-700
	15-30	0.9	1.1	2.0	2.5	-0.5	1.3	1.5	2900	3400	-500
	30-60	1.4	1.8	2.9	8.0	-5.1	0.5	0.8	2200	3600	-1300
		Totals		9.4	15.9	-6.5			9000	11600	-2500
650, wet, N^+, Rep II											
IIW2	0-15	2.5	3.2	5.4	7.0	-1.6	1.6	1.8	3500	3900	-400
	15-30	1.8	1.4	3.8	3.2	0.6	1.4	1.5	3200	3400	-200
	30-60	1.1	2.3	2.5	10.2	-7.7	0.5	0.6	2200	2700	-400
		Totals		11.7	20.4	-8.7			8900	10000	-1000

Table 6. Daytime, nighttime, and whole day mean chamber CO_2 concentrations and the corresponding standard deviations of the individual observations for the entire season of the 1987 CO_2-WATER-NITROGEN experiment.

		TREATMENT			
		Ambient		650	
Rep	Irrigation	N-	N+	N-	N+
Daytime:		$\mu\ell\ \ell^{-1}$			
I	wet	344±38	343±40	627±75	641±102
II	wet	-	340±40	641±76	627±84
I	dry	346±40	339±40	627±71	641±69
II	dry	345±38	353±43	622±75	614±69
Average over reps, irrigation, and nitrogen:		344±40		630±79	
Nighttime:					
I	wet	382±52	383±52	647±72	673±101
II	wet	-	383±58	649±76	652±97
I	dry	386±57	374±51	644±67	653±68
II	dry	383±57	399±66	642±82	648±86
Average over reps, irrigation, and nitrogen:		385±57		651±83	
Whole (24 hr) day:					
I	wet	361±49	361±50	636±75	656±103
II	wet	-	360±54	645±76	639±91
I	dry	365±53	355±48	635±70	647±69
II	dry	362±51	374±59	631±79	630±79
Average of reps, irrigation, and nitrogen:		363±52		639±82	

Table 7. Mean chamber CO_2 concentrations and the standard errors of the means, as measured with a LI-COR 6200 Portable Photosynthesis System near midday on 20 days during the growing season of the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over reps, irrigation, nitrogen and day-of-year, of which only the latter was a significant factor. The leaf number is the sequence number showing the order in which the measurements were taken, 1 being closest to the door.

Leaf No.	CO_2 TREATMENT			
	Ambient	650	±SEM	n
	- - - - - - $\mu\ell\ \ell^{-1}$	- - - -		
1	358	753	5	160
2	356	708	5	160
3	354	653	5	160
Means over leaves	356	706	15	480

Table 8. Final harvest data from open-topped enclosures with CO_2 enrichment (C+) to 650 ppm or ambient (C-) CO_2; and 231 kg/ha nitrogen added (N+) or no additional nitrogen during the year (N-). Data are averages of $3m^2$ harvested on October 15, 1987 (day 288) for each of the two replications.

Carbon Dioxide	650ppm (C+)								Ambient (C-)							
Irrigation	WET				DRY				WET				DRY			
Fertility	N+		N-		N+		N-		N+		N-		N+		N-	
Replication	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
Plants/m^2	14	15	13	15	13	14	15	15	15	15	14	15	15	14	15	15
Plant Ht. (cm)	82	57	74	61	55	57	69	61	65	57	47	47	42	51	51	47
Bolls/m^2	173	122	131	106	151	144	114	102	110	104	79	86	99	93	72	72
Tot.Top D.W.(g/m^2)	1001	819	721	502	820	720	627	536	668	590	392	472	525	441	364	303
Root Dry Wt. (g/m^2)	(No Data Collected)															
Ave.Top DW (g/m^2)	910		612		770		582		629		432		483		334	
Rel. CO_2 Effect	1.45		1.42		1.59		1.74		1.00		1.00		1.00		1.00	
Lint Wt. (g/m^2)[1]	168	139	138	93	128	116	112	100	157	113	79	102	102	77	77	64
Seed Wt. (g/m^2)	287	209	205	139	196	179	165	142	229	177	115	151	148	117	110	98
Average (g/m^2)	248		172		188		154		203		133		133		104	
Rel. CO_2 Effect	1.22		1.29		1.41		1.48		1.00		1.00		1.00		1.00	
% Lint	40	40	40	40	40	39	40	41	41	39	41	40	41	40	41	40
Seed Cotton(g/m^2)[2]	590	402	399	316	443	432	349	309	414	381	236	285	315	299	227	207
Average (g/m^2)	496		358		438		329		398		261		307		217	
Rel. CO_2 Effect	1.25		1.37		1.43		1.52		1.00		1.00		1.00		1.00	
Seed Index (g/100)	10.0	10.4	9.9	9.2	10.5	10.7	8.7	9.7	9.8	10.0	7.5	9.0	9.9	10.5	10.0	10.3
Harvest Index[3]	59	49	55	63	54	60	56	58	62	65	60	60	60	68	62	68

[1] Does not include weight of green, unopened bolls at time of harvest.

[2] Includes estimated seed cotton weight for green bolls at time of harvest.

[3] Seed cotton weight/top dry weight X 100.

Table 9. Leaf area index (LAI) and leaf area per boll (LAI/B) on various sampling days during 1987 in the CO_2-Water-Nitrogen experiment.

Day of Year	650 $\mu\ell/\ell$ CO_2				Ambient CO_2			
	N+		N-		N+		N-	
	LAI	LA/B	LAI	LA/B	LAI	LA/B	LAI	LA/B
		cm^2/boll		cm^2/boll		cm^2/boll		cm^2/boll
For the wet plots:								
156	0.3	-	0.3	-	0.4	-	0.4	-
160	0.5	-	0.3	-	0.3	-	0.4	-
167	0.8	1400	0.8	390	0.4	-	0.5	220
174	1.0	540	1.1	260	1.4	250	0.8	230
181	1.3	330	0.7	200	1.1	390	1.0	320
188	1.0	290	1.0	240	2.3	250	1.1	160
195	1.4	230	0.9	240	1.3	225	0.8	210
202	2.2	155	0.6	160	1.4	240	1.0	310
209	1.8	170	1.0	310	1.5	110	0.7	780
216	1.8	240	1.0	580	2.1	1430	1.3	840
223	4.2	210	2.7	240	4.3	375	2.2	570
230	1.7	305	2.6	430	2.3	-	1.7	-
237	2.7	155	2.4	230	2.5	400	1.1	255
For the dry plots:								
156	0.3	-	0.5	-	0.5	-	0.3	-
160	0.5	-	0.4	-	0.3	-	0.5	-
167	0.5	-	0.7	1400	0.5	270	1.0	1725
174	0.8	220	1.2	310	0.6	205	0.5	410
181	0.5	290	1.3	270	0.4	315	0.5	385
188	0.7	160	0.7	235	0.7	215	0.8	250
195	1.1	220	0.8	440	1.2	195	1.1	305
202	2.5	220	0.6	270	1.1	300	0.8	210
209	2.0	160	0.7	590	1.2	375	1.0	220
216	1.5	250	1.6	760	1.0	480	1.0	385
223	2.5	265	1.3	740	1.9	410	1.8	530
230	2.0	270	2.0	410	1.7	275	1.2	960
237	1.4	210	1.4	130	-	-	0.9	140

Table 10. Percentage increase in seed cotton yield due to a near-doubling of CO_2 under well-watered (wet) and water-stressed (dry) treatments and under low (no added N) and more normal (added nitrogen) levels of nitrogen fertilizer for 5 years of experiments with open-topped chambers at Phoenix, AZ.

Year	ADDED NITROGEN		NO ADDED NITROGEN	
	Wet	Dry	Wet	Dry
	- - - - - - - - -%- - - - - - - - - - -			
83	63	-	-	-
84	94	77	-	-
85	52	104	-	-
86	48	70	70	51
87	25	43	37	52
Ave.	56	74	54	52

Table 11. Mean petiole NO_3^- nitrogen concentrations for the 1987 CO_2-WATER-NITROGEN Experiment. Means not followed by the same letter are significantly different at the 0.05 level as determined by least significant difference following F test. The first order interactions with biweeks were also significant.

Irrigation X CO_2 X Nitrogen Interaction

dry				wet			
Ambient		650		Ambient		650	
N^-	N^+	N^-	N^+	N^-	N^+	N^-	N^+
mg/g							
1.69c	3.04b	0.68d	2.09c	0.72d	4.13a	0.65d	1.76c

CO_2 X Nitrogen

Ambient		650	
N^-	N^+	N^-	N^+
mg/g			
1.21bc	3.59a	0.66c	1.92b

Irrigation X Nitrogen

dry		wet	
N^-	N^+	N^-	N^+
mg/g			
1.18b	2.40a	0.69b	3.11a

Irrigation X CO_2

dry		wet	
Amb.	650	Amb.	650
mg/g			
2.37a	1.22b	2.43a	1.37b

Main Effects

Irrigation		CO_2		Nitrogen	
dry	wet	Amb.	650	N^-	N^+
mg/g					
1.79a	1.90a	2.40a	1.29b	0.94b	2.76a

Table 12. Mean net leaf photosynthesis for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over 2 reps, days, 3 leaves, and the other treatments, thus making the number of observations per mean equal to 24 times the number of sampling days. Means not followed by the same letter are significantly different at the 0.05 probability level from our analysis of variance F test considering the sampling days to be repeated measure sub-samples. The numbers in parentheses are the percentage change due to CO_2 enrichment. For the 2-day-after-irrigation data, the nitrogen treatment approached significance (0.063). Also, the interactions of sampling days with irrigation, and with CO_2 were significant. For the 6-day-after-irrigation data, the irrigation treatment approached significance (0.088). Also, the interactions of sampling days with irrigation, with irrigation by CO_2, with nitrogen, with nitrogen by irrigation, and with CO_2 by nitrogen were significant.

Days Since Irrig.	No. Obs.	TREATMENT					
		Irrigation		CO_2		NITROGEN	
		Dry	Wet	Amb.	650	N^-	N^+
		μ mol m^{-2} s^{-1}					
2	216	39.2a	38.0a	31.5a	45.7b (45%)	37.7a	39.5a
6	168	30.4a	33.4a	25.1a	38.7b (54%)	32.4a	31.5a

Table 13. Mean stomatal conductances for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over 2 reps, days, 3 leaves, and the other treatments, thus making the number of observations per mean equal to 24 times the number of sampling days. Means not followed by the same letter are significantly different at the 0.05 probability level from our analysis of variance F test considering the sampling days to repeated measure sub-samples (Table 10 of Kimball et al., 1986). The numbers in parentheses are the percentage change due to CO_2 enrichment. For the raw 6-days-after-irrigation data, the CO_2 treatment approached significance (0.066) and the interaction of irrigation with day of year was significant. For the adjusted 6-days-after-irrigation data, the interactions of both irrigation and nitrogen with day of year were significant.

		TREATMENT					
Days Since	No.	Irrigation		CO_2		NITROGEN	
Irrig.	Obs.	Dry	Wet	Amb.	650	N^-	N^+
		cm/s					
Raw:							
2	216	3.51a	3.51a	3.89a	3.13b (-20)	3.54a	3.48a
6	168	1.26a	1.89a	1.72a	1.43a (-17)	1.70a	1.45a
Adjusted following Idso et al. (1987):							
2	216	7.38a	9.05a	9.65a	6.78b (-30)	8.32a	8.10a
6	168	2.69a	4.51a	3.95a	3.25b (-18)	3.94a	3.27a

Table 14. List of measurement days and open-top chamber and cotton canopy characteristics used in the computation of canopy net photosynthesis.

Item	CHAMBER			
	IW3	IIW3	IW1	IIW2
CO_2	Ambient	Ambient	650	650
Irrigation	wet	wet	wet	wet
Nitrogen	N^+	N^+	N^+	N^+
Rep	I	II	I	II
Measurement Dates				
3 Sep 87		X		X
9 Sep 87		X		X
10 Sep 87	X		X	
11 Sep 87		X		X
Flow Rates (m^3/s)	1.34	1.21	.81	1.15
Leaf Area Index*	2.77	2.53	2.99	1.93

* Sampled on 25 August 1988 for IW3 and IW1 and on 18 August 1988 for IIW3 and IIW2.

Table 15. Characteristics of the regression equations relating cotton net photosynthesis, P ($\mu mol\ m^{-2}\ s^{-1}$), to photosynthetic photon flux, I ($\mu mol\ m^{-2}\ s^{-1}$) in Figures 26 - 29. The equations are quadratic of the form $P = b_o + b_1 I + b_2 I^2$.

	PHOTOSYNTHETIC SURFACE					
	Canopy		Leaf		Leaf x LAI	
Item	Amb.	650	Amb.	650	Amb.	650
No. of observations	24	22	24	23	24	23
b_o	-9.4	-18.2	-1.3	0.3	-3.8	0.7
b_1	0.0483	0.0832	0.0275	0.0361	0.00728	0.0734
b_2	-1.58E-5	-2.89E-5	-4.89E-6	-7.88E-6	-1.38E-5	-9.85E-6
r^2	0.75	0.51	0.96	0.90	0.97	0.81
SE of P estimate	7.2	17.6	2.0	3.6	4.8	12.2
SE of b_1	0.0117	0.038	0.0036	0.0087	0.0086	0.029
SE of b_2	6.80E-6	2.15E-5	2.59E-6	5.95E-6	6.05E-6	2.00E-5
P@ 1500 $\mu mol\ m^{-2} s^{-1}$	27.5	41.6	28.9	36.7	74.4	88.5
% increase from CO_2		+51		+27		+19

Table 16. Effect of soil moisture (H_2O), carbon dioxide (CO_2), and Nitrogen (Nit) on stomatal density, epidermal cell density, and stomatal index of upper and lower leaf surfaces of cotton.

		Probability of Greater F Value		
Source	d.f.	Stomatal Density	Epidermal Cell Density	Stomatal Index
H_2O	1	.43	.03 **	.18
Leaf Surface	1	.01 **	.01 **	.01 **
CO_2	1	.22	.10	.23
Nit	1	.04 **	.09 *	.18
CO_2 X Nit	1	.01 **	.04 **	.13
CO_2 X Surface	1	.77	.69	.25
CO_2 X H_2O	1	.93	.14	.41
H_2O X Nit	1	.26	.73	.39
H_2O X Surface	1	.79	.78	.31
Nit X Surface	1	.56	.59	.37
Error	13			
CV		12	9	12

*, ** Significant at 0.10 and 0.05 level of probability, respectively.

Table 17. Mean effects of CO_2 level, irrigation level, and nitrogen fertilizer level on stomatal density, epidermal cell density, and stomatal index of cotton. Data collected on 22 September 1987. The numbers in parentheses are the percentage change due to CO_2.

Leaf Surface	Irrigation		CO_2		Nitrogen	
	Dry	Wet	Amb	640	N-	N+
-- Stomatal Density (stomates per mm^2) --						
Adaxial	136	132	132	140	144	128
Abaxial	268	260	256	272	276	252
			(+6%)			
-- Epidermal Cell Density (epidermal cells per mm^2) --						
Adaxial	908	828	832	904	888	848
Abaxial	1120	1056	1064	1108	1124	1048
			(+6%)			
-- Stomatal Index -- -- (stomates/(stomates + epidermal cells)) x 100 --						
Adaxial	13.2	13.8	13.5	13.4	13.9	13.1
Abaxial	19.2	23.5	19.4	19.2	23.4	19.3
			(-1%)			

Table 18. Mean cotton leaf water potentials (LWP) for the main irrigation, CO_2 and nitrogen fertilizer effects for the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over 2 reps, 2 leaves per rep, biweeks, and the other treatments, thus making the number of observations per mean equal to 16 times the number of biweekly sampling periods. Means not followed by the same letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly intervals to be repeated measure subsamples. For the noon, 6-days-after-irrigation data the irrigation x nitrogen interaction showed significantly greater effect of the nitrogen in the dry treatment than in the wet.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			- - - - - - - - - -	- - - - -	- % - - - -		- - - - -	- - - -
2	Predawn	128	-1.36a	-1.28a	-1.30a	-1.33a	-1.33a	-1.30a
2	Noon	112	-1.89a	-1.76a	-1.85a	-1.79a	-1.83a	-1.82a
6	Predawn	112	-1.46a	-1.31a	-1.37a	-1.41a	-1.41a	-1.37a
6	Noon	112	-2.12a	-1.85b	-2.02a	-1.95b	-2.05a	-1.92b

Table 19. Mean relative leaf water contents (RLWC) of cotton for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over 2 reps, biweeks, and the other treatments, thus making the number of observations per mean equal to 8 times the number of biweek sampling periods. Means not followed by the same letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly sampling intervals to be repeated measure subsamples.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			%					
2	Predawn	64	77.9a	82.5b	80.0a	80.4a	80.1a	80.3a
2	Noon	48	79.3a	80.4a	80.0a	79.8a	81.1a	78.6a
6	Predawn	64	77.7a	82.8b	80.4a	80.1a	81.3a	79.3a
6	Noon	48	74.9a	79.5a	77.1a	77.2a	77.7a	76.7a

Table 20. Mean cotton leaf dry matter contents (DMC) for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over 2 reps, biweeks, and the other treatments, thus making the number of observations per mean equal to 8 times the number of biweek sampling periods. Means not followed by the same letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly intervals to be repeated measure subsamples.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			%					
2	Predawn	56	23.7a	23.3a	21.8a	25.1b	23.5a	23.4a
2	Noon	56	24.0a	24.4a	23.1a	25.3b	23.8a	24.6a
6	Predawn	56	23.2a	22.4a	21.2a	24.4b	22.6a	23.1a
6	Noon	48	24.3a	23.6a	22.3a	25.7b	23.6a	24.4a

Table 21. Mean cotton specific leaf weights (SLW) for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1987 CO_2-WATER-NITROGEN experiment. The means are averages over 2 reps, biweeks, and the other treatments, thus making the number of observations per mean equal to 8 times the number of biweek sampling periods. Means not followed by the same letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly intervals to be repeated measure subsamples. For the noon, 2-days-after-irrigation data and the predawn, 6-days-after-irrigation data the irrigation x CO_2 interaction showed significantly greater effect of the CO_2 in the wet plots than in the dry plots.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			- - - - - - - - - - - $g\ m^{-2}$ - - - - - - - - - - -					
2	Predawn	64	67.1a	61.2a	55.7a	72.6b	64.3a	64.0a
2	Noon	48	65.6a	61.4a	57.3a	69.7b	63.4a	63.6a
6	Predawn	64	64.5a	58.9a	54.1a	69.3b	60.6a	62.8a
6	Noon	64	64.1a	60.3a	53.7a	70.7b	61.5a	63.0a

Table 22. Irrigation and Rain amounts for the 1987 FIZZ-FACE experiment. Also included are the hours of fizz-water (CO_2) applications.

DATE	DAY of YEAR	IRRIG. (I) or RAIN (R)	TREATMENT						
			CONTROL	FACE				FIZZ	
				REP 1	REP 2	REP 3	REP 4	H_2O mm	CO_2 hrs.
30-APR	120	R	0.3	0.3	0.3	0.3	0.3	0.3	
06-May	126	I^z	150.0	150.0	150.0	150.0	150.0	150.0	
11-May	131	R	1.5	1.5	1.5	1.5	1.5	1.5	
15-May	135	R	0.3	0.3	0.3	0.3	0.3	0.3	
29-May	149	I	3.9	6.8	8.6	7.1	6.7	8.4	2.78
04-Jun	155	I	8.6	7.7	7.4	7.5	7.3	4.3	3.58
05-Jun	156	I	7.2	7.7	7.4	7.4	7.2	4.3	3.58
06-Jun	157	R	1.8	1.8	1.8	1.8	1.8	1.8	
11-Jun	162	I	7.0	6.4	7.6	6.9	6.9	27.6	8.85
12-Jun	163	I	7.0	6.4	7.6	6.9	6.9	27.5	8.85
13-Jun	164	I	7.0	6.4	7.6	6.9	6.9		
14-Jun	165	I	7.0	6.4	7.7	7.0	7.0		
15-Jun	166	I	6.9	6.5	7.7	7.0	7.0		
17-Jun	168	I	8.5	7.2	6.4	5.9	7.5	8.1^y	
18-Jun	169	I	8.5	7.2	6.4	5.9	7.5	8.1^y	
19-Jun	170	I	8.5	7.2	6.4	5.9	7.5	8.1^y	
20-Jun	171	I	8.5	7.2	6.4	5.9	7.5	8.1^y	
21-Jun	172	I	8.5	7.2	6.3	6.0	7.6	8.1^y	
22-Jun	173	I	8.7	7.0	6.3	6.0	7.6	7.9^y	
24-Jun	175	I	7.3	9.0	8.5	9.7	8.2	5.4^y	
25-Jun	176	I	7.3	9.0	8.5	9.7	8.2	5.4^y	
26-Jun	177	I	7.3	9.0	8.5	9.7	8.2	5.4^y	
27-Jun	178	I	7.3	9.0	8.5	9.7	8.2	5.4^y	
28-Jun	179	I	7.3	9.0	8.6	9.7	8.1	5.4^y	
29-Jun	180	I	7.0	9.1	8.6	9.6	8.1	5.3^y	
01-Jul	182	I	8.4	8.4	9.3	9.0	8.7	8.3^y	
02-Jul	183	I	8.4	8.4	9.3	9.0	8.7	8.3^y	
03-Jul	184	I	8.4	8.4	9.3	9.0	8.7	8.3^y	
04-Jul	185	I	8.4	8.4	9.3	8.9	8.7	8.2^y	
05-Jul	186	I	8.4	8.4	9.4	8.9	8.8	8.2^y	
06-Jul	187	I	8.6	8.4	9.4	8.9	8.8	8.2^y	
08-Jul	189	I	14.0	14.2	14.3	14.5	14.9	15.5	4.29
09-Jul	190	I	14.0	14.2	14.3	14.5	14.9	15.5	4.29
10-Jul	191	I	14.0	14.2	14.3	14.5	14.9	15.5	4.29
11-Jul	192	I	14.0	14.1	14.3	14.5	14.9	15.5	4.29
12-Jul	193	I	14.0	14.1	14.3	14.5	14.9	15.5	4.29
13-Jul	194	I	13.9	14.1	14.3	14.4	15.0	15.5	4.29
15-Jul	196	I	16.5	15.6	14.0	15.1	14.2	15.3	4.16
16-Jul	197	I	16.5	15.6	14.0	15.1	14.2	15.3	4.16
17-Jul	198	I	16.5	15.6	14.0	15.1	14.2	15.3	4.16
18-Jul	199	I	16.5	15.6	14.0	15.1	14.2	15.3	4.16
19-Jul	200	I	16.5	15.6	14.0	15.2	14.2	15.3	4.16
20-Jul	201	I	16.3	15.6	14.0	15.2	14.2	15.5	4.16
22-Jul	203	I	11.6	12.5	13.1	10.2	13.0	12.9	3.33
23-Jul	204	I	11.6	12.5	13.1	10.2	13.0	12.9	3.33
24-Jul	205	I	11.6	12.5	13.1	10.2	13.0	12.9	3.33
25-Jul	206	I	11.6	12.5	13.1	10.2	13.0	12.9	3.33
26-Jul	207	I	11.6	12.5	13.2	10.2	13.0	12.9	3.33
27-Jul	208	I	11.7	12.5	13.2	10.1	12.9	12.8	3.33
27-Jul	208	R	11.9	11.9	11.9	11.9	11.9	11.9	
28-Jul	209	R	1.3	1.3	1.3	1.3	1.3	1.3	
29-Jul	210	I	15.0	14.8	15.9	16.6	15.0	14.9	4.00
30-Jul	211	I	15.0	14.8	15.9	16.6	15.0	14.9	4.00
31-Jul	212	I	15.0	14.8	15.9	16.6	15.0	14.9	4.00
01-Aug	213	R	18.0	18.0	18.0	18.0	18.0	18.0	
01-Aug	213	I	15.0	14.8	15.9	16.6	15.0	14.9	4.01
02-Aug	214	I	15.0	14.9	15.9	16.6	15.0	14.9	4.01
03-Aug	215	I	15.1	14.9	16.0	16.7	15.1	14.9	4.01
05-Aug	217	R	12.7	12.7	12.7	12.7	12.7	12.7	
06-Aug	218	I	11.5	11.3	9.5	12.0	11.0	9.3	2.43
07-Aug	219	I	11.5	11.3	9.5	12.0	11.0	9.3	2.43
08-Aug	220	I	11.5	11.3	9.5	12.0	11.0	9.3	2.43
09-Aug	221	I	11.5	11.3	9.6	12.0	11.1	9.3	2.43

Table 22. (Continued) Irrigation and Rain amounts for the 1987 FIZZ-FACE experiment. Also included are the hours of fizz-water (CO_2) applications.

DATE	DAY of YEAR	IRRIG. (I) or RAIN (R)	TREATMENT						
				FACE				FIZZ	
			CONTROL	REP 1	REP 2	REP 3	REP 4	H_2O	CO_2
								mm	hrs.
10-Aug	222	I	11.4	11.3	9.6	12.1	11.1	9.4	2.43
11-Aug	223	R	7.9	7.9	7.9	7.9	7.9	7.9	
12-Aug	224	I	10.4	11.0	12.2	10.2	9.8	8.2	2.63
13-Aug	225	I	10.4	11.0	12.2	10.2	9.8	8.2	2.63
14-Aug	226	I	10.4	11.0	12.2	10.2	9.8	8.2	2.63
15-Aug	227	I	10.4	11.0	12.1	10.2	9.7	8.1	2.63
16-Aug	228	I	10.4	11.0	12.1	10.1	9.7	8.1	2.63
17-Aug	229	I	10.3	10.9	12.1	10.1	9.7	8.1	2.63
19-Aug	231	I	12.4	12.5	10.6	12.8	14.2	15.6	3.80
20-Aug	232	I	12.4	12.5	10.6	12.8	14.2	15.6	3.80
21-Aug	233	I	12.4	12.5	10.6	12.8	14.2	15.6	3.80
22-Aug	234	I	12.4	12.5	10.6	12.7	14.2	15.6	3.80
23-Aug	235	R	3.6	3.6	3.6	3.6	3.6	3.6	
23-Aug	235	I	12.4	12.5	10.5	12.7	14.2	15.6	3.80
24-Aug	236	R	3.0	3.0	3.0	3.0	3.0	3.0	
24-Aug	236	I	12.3	12.5	10.5	12.7	14.1	15.6	3.80
25-Aug	237	R	21.1	21.1	21.1	21.1	21.1	21.1	
27-Aug	239	I	9.3	7.5	9.2	8.6	6.8	4.9	1.18
28-Aug	240	I	9.3	7.5	9.2	8.6	6.8	4.9	1.18
29-Aug	241	I	9.3	7.5	9.2	8.6	6.8	4.9	1.18
30-Aug	242	I	9.3	7.5	9.3	8.6	6.8	4.9	1.18
31-Aug	243	I	9.1	7.4	9.3	8.7	6.7	4.9	1.18
02-Sep	245	I	11.8	13.8	13.3	13.1	13.0	11.3	2.91
03-Sep	246	I	11.8	13.8	13.3	13.1	13.0	11.3	2.91
04-Sep	247	I	11.8	13.8	13.3	13.1	13.0	11.3	2.91
05-Sep	248	I	11.8	13.8	13.2	13.1	13.0	11.3	2.91
06-Sep	249	I	11.8	13.8	13.2	13.2	13.0	11.3	2.91
07-Sep	250	I	11.7	13.8	13.2	13.2	13.1	11.5	2.91
09-Sep	252	I	11.3	10.5	11.8	10.4	13.4	11.3	2.93
10-Sep	253	I	11.3	10.5	11.8	10.4	13.4	11.3	2.93
11-Sep	254	I	11.3	10.5	11.8	10.4	13.4	11.3	2.93
12-Sep	255	I	11.3	10.4	11.7	10.4	13.4	11.3	2.93
13-Sep	256	I	11.3	10.4	11.7	10.3	13.4	11.3	2.93
14-Sep	257	I	11.3	10.4	11.7	10.3	13.5	11.3	2.93
16-Sep	259	I	11.3	11.3	11.8	11.5	9.8	11.9	3.05
17-Sep	260	I	11.2	11.3	11.7	11.5	9.7	11.9	3.05
		Totals	1176.6	1180.2	1188.3	1180.6	1189.6	1160.6	220.1

[y] Due to repair of carbonator, FIZZ plots received plain water between 17 June and 7 July.

[z] Applied by flooding in furrows. All other irrigations applied through drip tubing.

Table 23. Nitrogen applications to the FIZZ-FACE 1987 experiment. At first the fertilizer source was urea, and then it was uran-32 starting on 15 July.

	Day of Year	Face REP I		Face REP II		Face REP III		Face REP IV		FIZZ		CONTROL	
		NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-
		-kg N/ha-											
28-Apr	118	8.44		8.44		8.44		8.44		8.44		8.44	
17-Jun	168	5.37		8.49		6.16		4.62		4.75		1.89	
24-Jun	175	5.37		8.49		6.16		4.62		14.06		5.81	
02-Jul	183	5.37		8.49		6.16		4.62		9.27		3.94	
08-Jul	189	5.37		8.49		6.16		4.62		8.25		4.65	
15-Jul	196	5.91	1.89	9.36	2.99	6.79	2.17	5.09	1.63	9.16	2.93	5.08	1.62
23-Jul	204	5.91	1.89	9.36	2.99	6.79	2.17	5.09	1.63	9.60	3.07	4.77	1.52
29-Jul	210	5.91	1.89	9.36	2.99	6.79	2.17	5.09	1.63	9.70	3.10	4.70	1.50
06-Aug	218	5.91	1.89	9.36	2.99	6.79	2.17	5.09	1.63	9.36	2.99	4.94	1.58
13-Aug	225	7.10	2.27	7.49	2.39	6.79	2.17	6.11	1.95	7.21	2.30	7.15	2.28
19-Aug	231	7.10	2.27	7.49	2.39	6.79	2.17	6.11	1.95	7.21	2.30	7.15	2.28
27-Aug	239	7.10	2.27	7.49	2.39	6.79	2.17	6.11	1.95	7.21	2.30	7.15	2.28
02-Sep	245	5.91	1.89	9.36	2.99	6.79	2.17	5.09	1.63	7.21	2.30	7.15	2.28
		80.77	16.25	111.68	22.13	87.36	17.35	70.67	13.98	111.42	21.30	72.80	15.36
Totals for both forms		97.02		133.81		104.71		84.65		132.72		88.16	
Irrigated area (m^2):		1028		650		896		1195		369		532	

Table 24. Mean CO_2 concentrations and the associated standard deviations at the 75% plant height from 20 June through 19 September for the 1987 FIZZ/FACE experiment at Phoenix, Arizona.

AVERAGING INTERVAL	REP	TREATMENT CONTROL	FIZZ	FACE
		- - - - - μ ℓ/ℓ	- - - -	
09:00-10:00	I	348±34	360±42	346±38
	II	343±34	359±43	347±38
	III	348±36	357±55	346±40
	IV	348±36	362±53	349±44
	Average	347±35	360±48	347±40
12:00-13:00	I	340±35	345±36	456±94
	II	337±36	346±39	459±90
	III	351±47	357±38	434±71
	IV	338±40	345±39	446±88
	Average	342±40	348±38	449±86
Daytime	I	342±38	346±39	381±83
	II	340±36	345±39	380±81
	III	347±48	348±43	371±69
	IV	340±38	344±42	376±78
	Average	342±40	346±41	377±78
Nighttime	I	376±49	382±51	378±50
	II	370±47	367±45	375±50
	III	389±62	387±58	379±54
	IV	384±60	384±60	386±61
	Average	380±55	380±54	380±54
Whole Day	I	358±47	363±48	379±70
	II	354±44	355±43	377±69
	III	367±59	366±54	375±63
	IV	360±54	362±55	381±71
	Average	360±51	362±50	378±68

Table 25. Mean CO_2 concentrations and standard errors of means, as measured with a LI-COR 6200 Portable Photosynthesis System near midday on 9 days during the growing season of the 1987 FIZZ/FACE experiment. The means are averages over reps and day-of-year. Day-of-year was a significant factor as was the CO_2 x day-of-year interaction.

Leaf No.	CO_2 TREATMENT Control	FIZZ	FACE	±SEM	n
	- - - - - - - $\mu\ell\ \ell^{-1}$	- - - - - - -			
1	351	344	406	5	36
2	341	343	378	5	36
3	339	342	387	5	36
Means over leaves	343	343	391	3	108

Table 26. Mean CO_2 concentrations and the associated standard deviations at various heights for Rep IV from 20 June to 19 September for the 1987 FIZZ/FACE experiment at Phoenix, AZ.

AVERAGING INTERVAL	HEIGHT	TREATMENT CONTROL	FIZZ	FACE
		- - - - - - µℓ/ℓ - - - - - -		
09:00-10:00	1.8 m	352±38	353±37	352±39
	75%	348±36	362±53	349±44
	50%	348±57	369±54	353±56
	25%	351±35	394±96	361±73
12:00-13:00	1.8 m	344±41	343±38	357±40
	75%	338±40	345±39	446±88
	50%	339±38	351±41	490±122
	25%	341±39	366±50	569±160
Daytime	1.8 m	343±38	343±38	347±41
	75%	340±38	344±42	376±78
	50%	341±38	348±44	390±102
	25%	344±38	358±56	423±148
Nighttime	1.8 m	362±47	361±47	360±47
	75%	384±60	384±60	386±61
	50%	389±63	389±62	390±63
	25%	394±63	394±64	394±64
Whole Day	1.8 m	352±43	351±43	353±44
	75%	360±54	362±55	381±71
	50%	363±57	367±57	390±86
	25%	367±57	375±63	409±118

Table 27. Final harvest data from the open-field CO_2-release (FIZZ-FACE) studies. Data are averages of $5m^2$ harvested on 29 September - 1 October 1987 (day 272-274) for each of the four replications.

TREATMENT	Control (C)				FIZZ (Z)				FACE (A)			
REPLICATION	I	II	III	IV	I	II	III	IV	I	II	III	IV
Plant Height (cm)	70	79	85	90	93	86	84	95	88	91	79	82
Bolls/m^2 (Total)	78	82	83	93	90	111	88	95	103	100	82	106
Top Dry Wt (g/m^2)	493	473	401	466	535	608	534	657	643	553	508	647
Root Dry Wt (g/m^2)	(NO DATA COLLECTED)											
Ave. Top D.W. (g/m^2)		458				584				588		
Rel. CO_2 Effect		1.00				1.28				1.28		
Lint Wt (g/m^2)[1]	113	112	91	107	148	151	138	133	146	143	129	138
Seed Wt (g/m^2)	163	170	130	150	216	225	193	190	206	212	184	195
Average (g/m^2)		259				349				338		
Rel. CO_2 Effect		1.00				1.35				1.31		
% Lint	41	40	41	42	41	40	42	41	41	40	41	41
Seed Cotton (g/m^2)[2]	307	302	312	377	394	419	382	382	435	394	327	422
Average (g/m^2)		325				394				395		
Rel. CO_2 Effect		1.00				1.21				1.22		
Seed Index (g/100)	10.3	9.3	10.4	10.0	10.3	10.7	10.8	10.1	10.8	10.5	10.3	10.9
Harvest Index[3]	62	64	78	81	74	69	72	58	68	71	64	65

[1] Does not include weight of green, unopened bolls at time of harvest.

[2] Includes estimate of seed cotton in green bolls at the time of harvest.

[3] Seed cotton weight/top dry weight X 100.

Table 28. Leaf area index (LAI) and leaf area per boll (LA/B) on various sampling days in 1987 from the FIZZ/FACE experiment. The data are averages over four reps.

Day of Year	FACE LAI	FACE LA/B cm^2/boll	FIZZ LAI	FIZZ LA/B cm^2/boll	CONTROL LAI	CONTROL LA/B cm^2/boll
158	0.3		0.3		0.3	
161	0.4		0.4		0.5	
168	0.6		0.7	2400	0.7	9300
175	0.9	680	1.1	775	0.9	1480
182	1.1	340	1.8	540	1.5	390
189	1.2	190	1.7	270	1.2	250
196	1.7	175	2.3	180	1.4	170
203	1.5	170	2.2	190	1.3	210
210	2.1	200	2.5	250	1.9	240
217	2.2	340	2.4	300	1.9	310
224	2.8	330	4.2	450	2.7	920
231	2.3	840	3.2	750	2.1	870
238	3.0	2500	3.3	-	3.9	3100
245	3.0	2400	4.7	2100	3.1	1650
252	2.4	1940	3.8	1250	3.5	1450

Table 29. Elemental analysis of cotton leaf blades sampled 23 July 1987 from Rep II of the FIZZ/FACE experiment, as analyzed (and interpreted) by IAS Laboratories, Phoenix, Arizona. Each sample was a composite of 10 leaf blades taken from the top of the canopy. The letters following the numeric values are interpretive codes, as defined in the footnote[1]

Element		TREATMENT					
		Control		FIZZ		FACE	
N	(g/kg)	27	C	34	A	27	C
P	(g/kg)	5.7	A	3.1	A	5.0	A
K	(g/kg)	22	A	22	A	25	A
Ca	(g/kg)	45	H	47	H	46	H
Mg	(g/kg)	8.0	A	8.4	A	7.9	A
S	(g/kg)	19	H	19	H	19	H
Na	(g/kg)	1.4	A	2.1	H	1.5	A
Fe	(mg/kg)	175	A	195	A	180	A
Zn	(mg/kg)	21	C	21	C	19	D
Mn	(mg/kg)	69	A	95	A	81	A
Cu	(mg/kg)	10	A	10	A	9.9	A
B	(mg/kg)	195	A	195	A	185	A

[1] D (Deficient): Visual symptoms of deficiency should be showing. If corrected early in most crops, yields will benefit.

C (Critical): Visual deficiency symptoms may or may not be present, but fertilization with this element is likely to increase yield.

A (Adequate): Plant contains enough of element for maximum yield. Ideally, all elements would be at this level.

H (High): This level of concentration indicates a luxury or extravagant amount of this element.

T (Toxic): There are probably visual symptoms of toxicity present. Yields would be depressed by elements in this concentration range.

Table 30. Mean net photosynthesis, "raw" stomatal conductance, and "adjusted" stomatal conductance observed near midday on 9 days of the 1987 FIZZ/FACE experiment. The means are averages over 3 leaves per plot, 4 replicate plots, and 9 days. Means not followed by the same letter are significantly different at the 0.05 probability level using LSD after F test.

Item	n	CO_2 TREATMENT CONTROL	FIZZ	FACE
Net Photosynthesis (μmol m^{-2} s^{-1})	108	26.5a	26.4a	30.4b
"Raw" stomatal conductance (cm s^{-1})	96	2.92a	2.90a	2.90a
"Adjusted" stomatal conductance following Idso et al. (1987) (cm s^{-1})	96	8.21a	7.56a	11.6a

Table 31. Beet armyworm growth on host cotton plants grown at ambient and 650 $\mu\ell \cdot \ell^{-1}$ CO_2 treatments and high and low fertilizer treatments.

	CO_2 TREATMENT									
	650 CO_2				Ambient CO_2			Total		
Fertilizer	No.	mg	± SEM		No.	mg	± SEM	No.	mg	± SEM
High	30	89.0	2.5	*	51	98.6	3.0	81	95.0	2.1
									#	
Low	6	81.9	12.6		8	85.5	6.1	14	84.0	6.1
Group	36	87.8	2.9	*	59	96.8	2.7			

* $P \leq 0.05$; # $P = 0.058$

Table 32. Growth of beet armyworm females and males on host cotton grown at ambient and 650 $\mu\ell/\ell$ CO_2 and high and low fertilizer treatments.

	High Fertilizer								Low Fertilizer					
	650 CO_2				Ambient CO_2			650 CO_2			Ambient CO_2			
Sex	No.	mg	± SEM		No.	mg	± SEM	No.	mg	± SEM	No.	mg	± SEM	
Female	20	87.3	3.2	*	27	101.0	4.3	3	95.7	21.5	5	93.4	5.5	
Male	10	92.3	4.3		24	95.8	4.0	3	68.1	11.8	3	72.5	10.4	
Group	30	89.0	2.5	*	51	98.6	3.0	6	81.9	12.6	8	85.5	6.1	

* $P \leq 0.05$

Table 33. Beet armyworm development time on host cotton plants grown at ambient and 650 $\mu\ell\ \ell^{-1}$ CO_2 treatments and high and low fertilizer treatments.

	CO_2 TREATMENT									
	650 CO_2				Ambient CO_2			Total		
Fertilizer	No.	Days	± SEM		No.	Days	± SEM	No.	Days	± SEM
High	30	13.7	0.5	**	56	12.3	0.3	86	12.8	0.3
								***		
Low	7	18.3	1.7		7	15.1	1.6	14	16.7	1.2
Group	37	14.59	0.6	**	63	12.6	0.3			

** $P \leq 0.01$; *** $P \leq 0.001$

Table 34. Development time of beet armyworm females and males on host cotton plants grown at ambient and 650 $\mu\ell/\ell$ CO_2 and high and low fertilizer treatments.

	High Fertilizer								Low Fertilizer							
	650 CO_2				Ambient CO_2				650 CO_2				Ambient CO_2			
Sex	No.	Days	±	SEM	No.	Days	±	SEM	No.	Days	±	SEM	No.	Days	±	SEM
Female	20	14.2		0.7 *	27	12.4		0.5	4	16.5		1.7	5	16.2		2.2
Male	10	12.8		0.4	29	12.1		0.3	3	20.7		3.2	2	12.5		0.5
Group	30	13.7		0.5 **	56	12.3		0.3	7	18.3		1.7	7	15.1		1.6

* $P \leq 0.05$; ** $P \leq 0.01$

Table 35. Beet armyworm survival on host cotton plants grown at ambient and 650 $\mu\ell\ \ell^{-1}$ CO_2 treatments and high and low fertilizer treatments.

Fertilizer	650 CO_2			Ambient CO_2	
	%	No.		%	No.
High	19.1	(30/157)	***	41.6	(57/137)
		**			***
Low	4.9	(7/143)		5.4	(7/129)

** $P \leq 0.01$; *** $P \leq 0.001$

Table 36. Percentage of surviving beet armyworm larvae that were male and female after rearing on cotton grown at ambient and 650 $\mu\ell/\ell$ CO_2 and at the high fertilizer treatment.

Sex	650 CO_2		Ambient CO_2	
	%	No.	%	No.
Female	66.7	(20/30)	48.2	(27/56)
	*			
Male	33.3	(10/30)	51.8	(29/56)

* $P \leq 0.05$

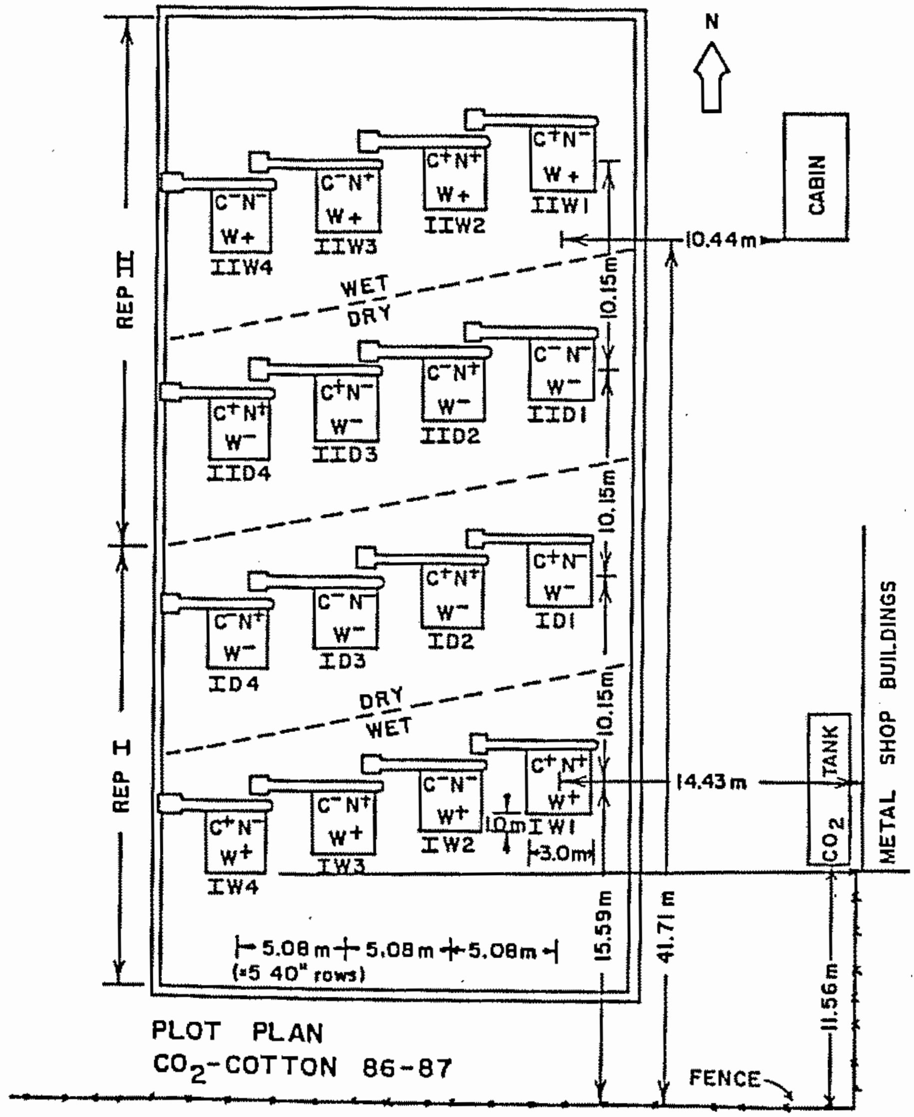

Figure 1. Plot plan for the 1987 CO_2/WATER/NITROGEN experiment (which was the same as that for 1986) showing the arrangement of the open-top chamber plots with 2 reps (I and II), ambient (C^-) and 650 $\mu\ell\ \ell^{-1}$ (C^+) CO_2 treatments, well-watered (W^+) and water-stress (W^-) irrigation treatments, and none added (N^-) and added (N^+) nitrogen treatments.

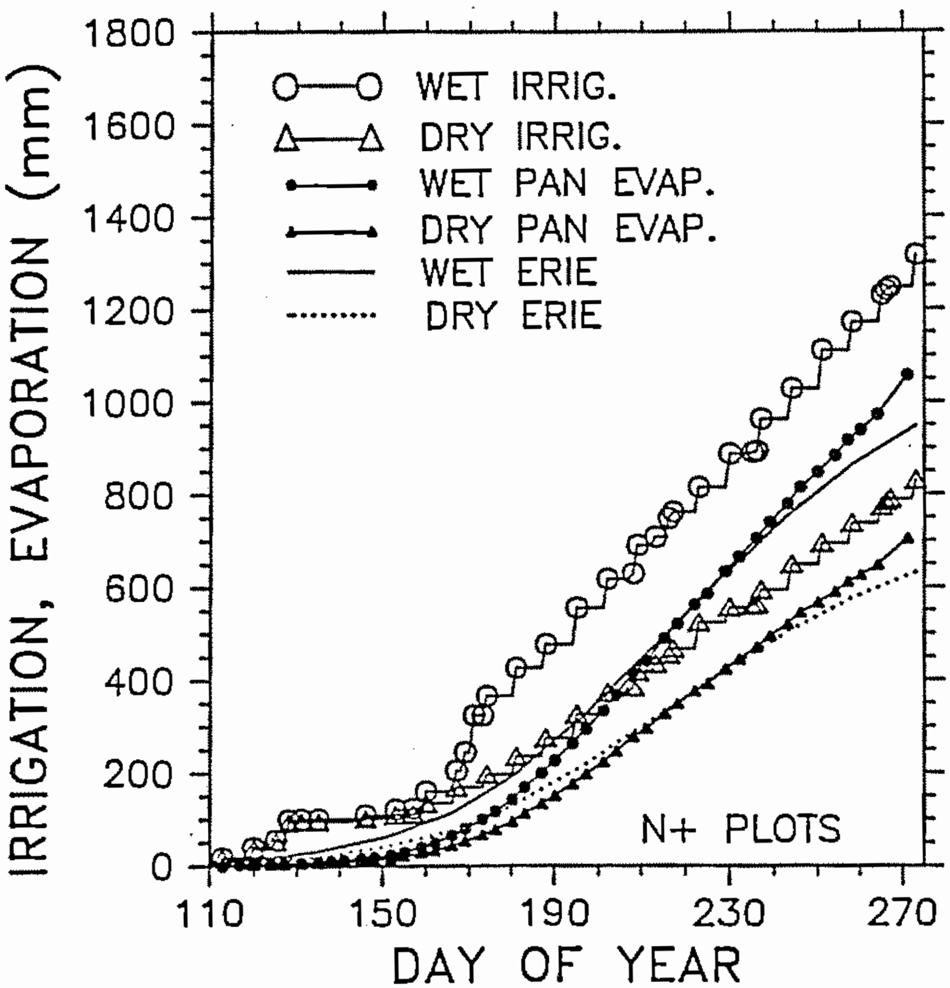

Figure 2. Amounts of irrigation and rainfall applied to the wet and dry plots that received added nitrogen (N^+) for the CO_2-cotton 1987 experiment. Also plotted are the measured pan evaporation (X LAI/3) and the Erie et al. (1981) consumptive use curve for cotton for comparison with the wet plots as well as 2/3 of those amounts for comparison with the dry plots.

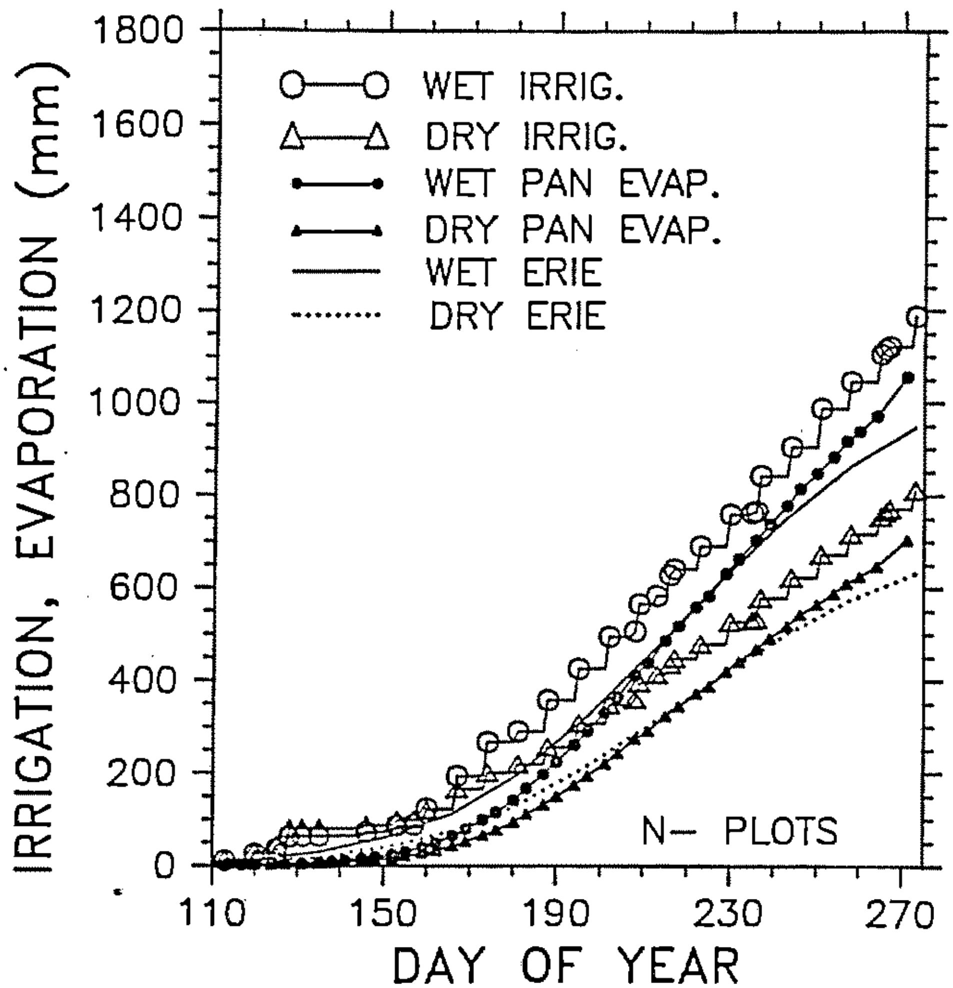

Figure 3. Amounts of irrigation and rainfall applied to the wet and dry plots that received no added nitrogen (N^-) for the CO_2-cotton 1987 experiment. Also plotted are the measured pan evaporation (X LAI/3) and the Erie et al. (1981) consumptive use curve for cotton for comparison with the wet plots as well as 2/3 of those amounts for comparison with the dry plots.

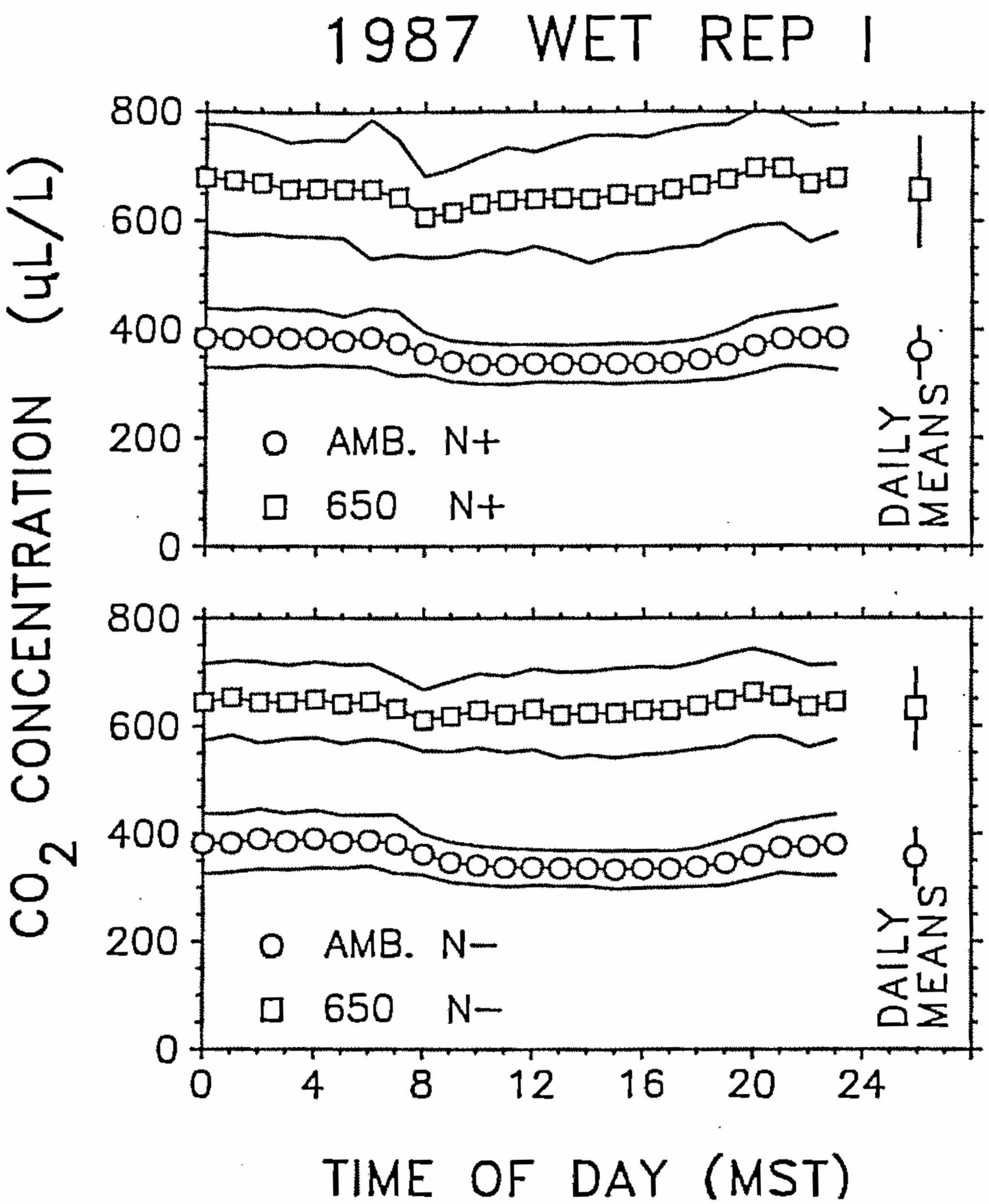

Figure 4. Diurnal pattern of the mean CO_2 concentration for the wet-Rep I chambers in 1987. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

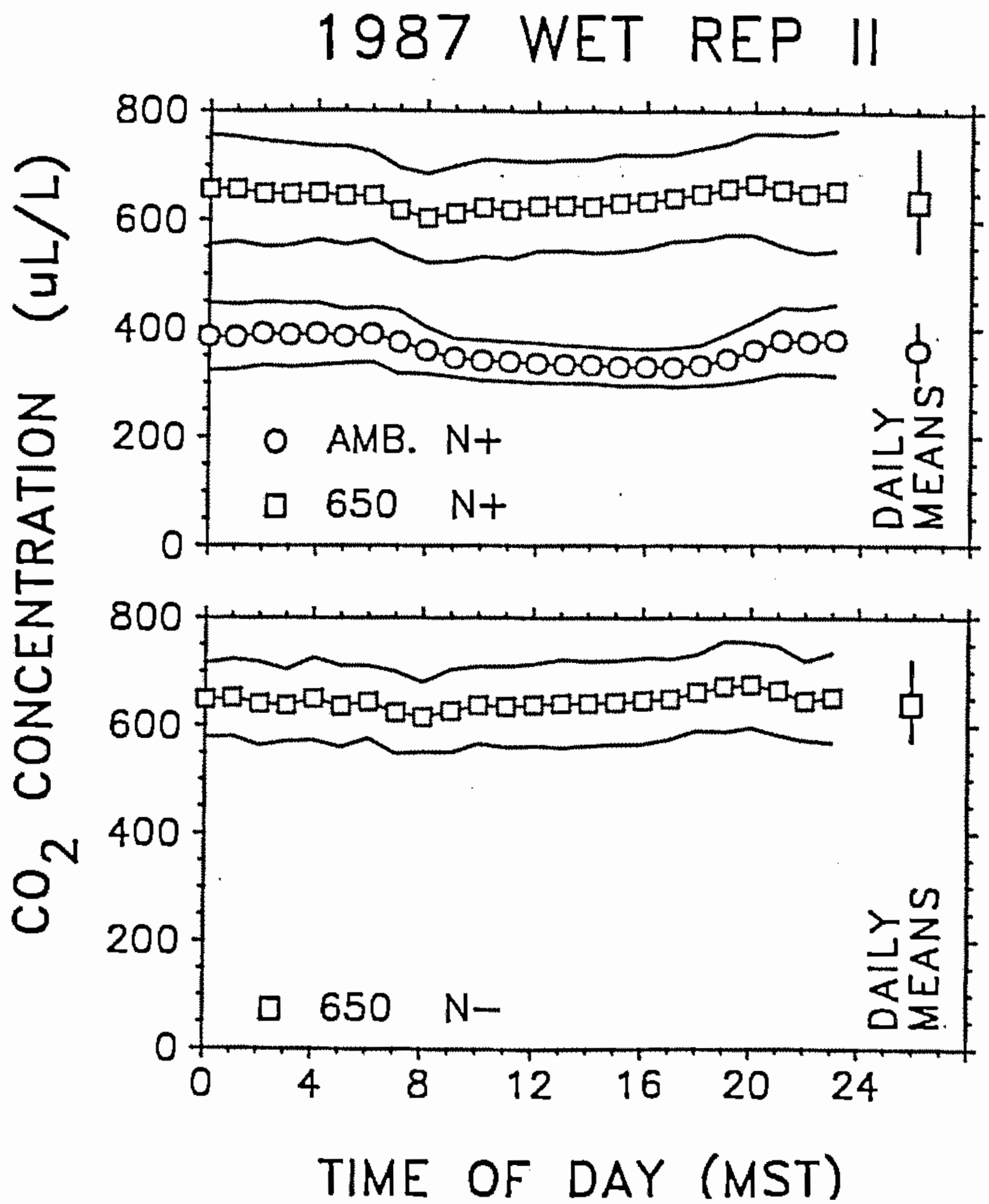

Figure 5. Diurnal pattern of the mean CO_2 concentration for the wet-Rep II chambers in 1987. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

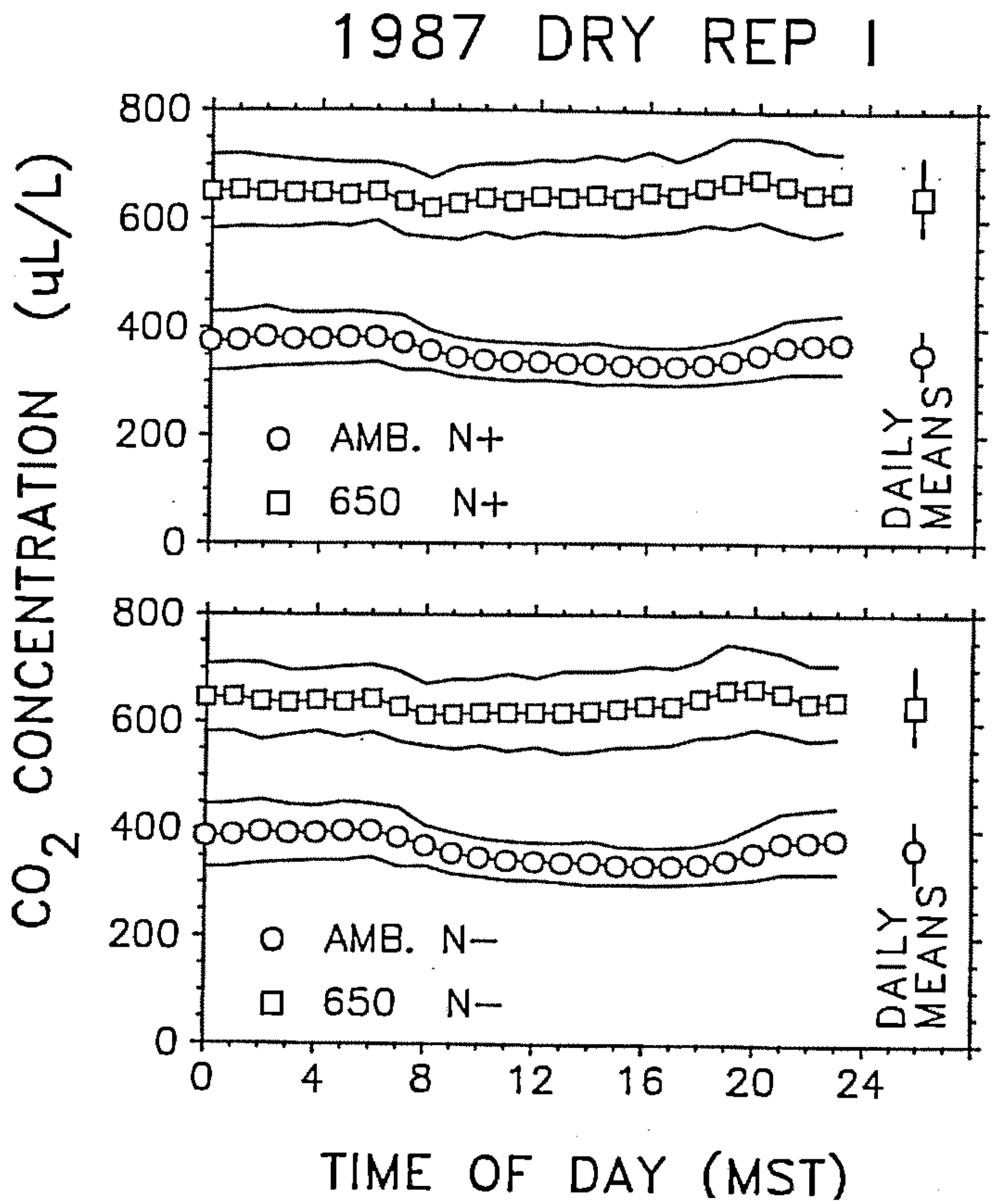

Figure 6. Diurnal pattern of the mean CO_2 concentration for the dry-Rep I chambers in 1987. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

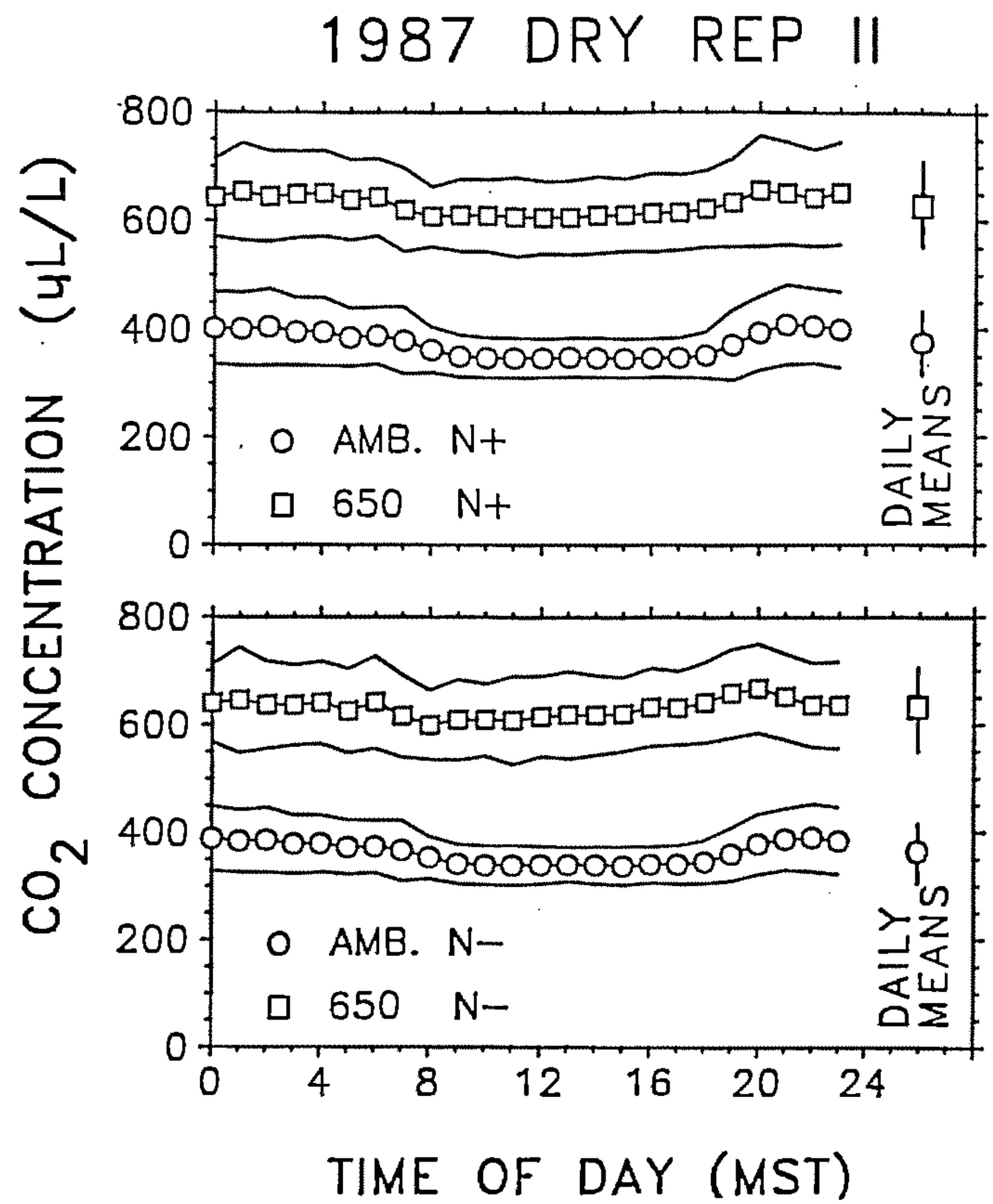

Figure 7. Diurnal pattern of the mean CO_2 concentration for the dry-Rep II chambers in 1987. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

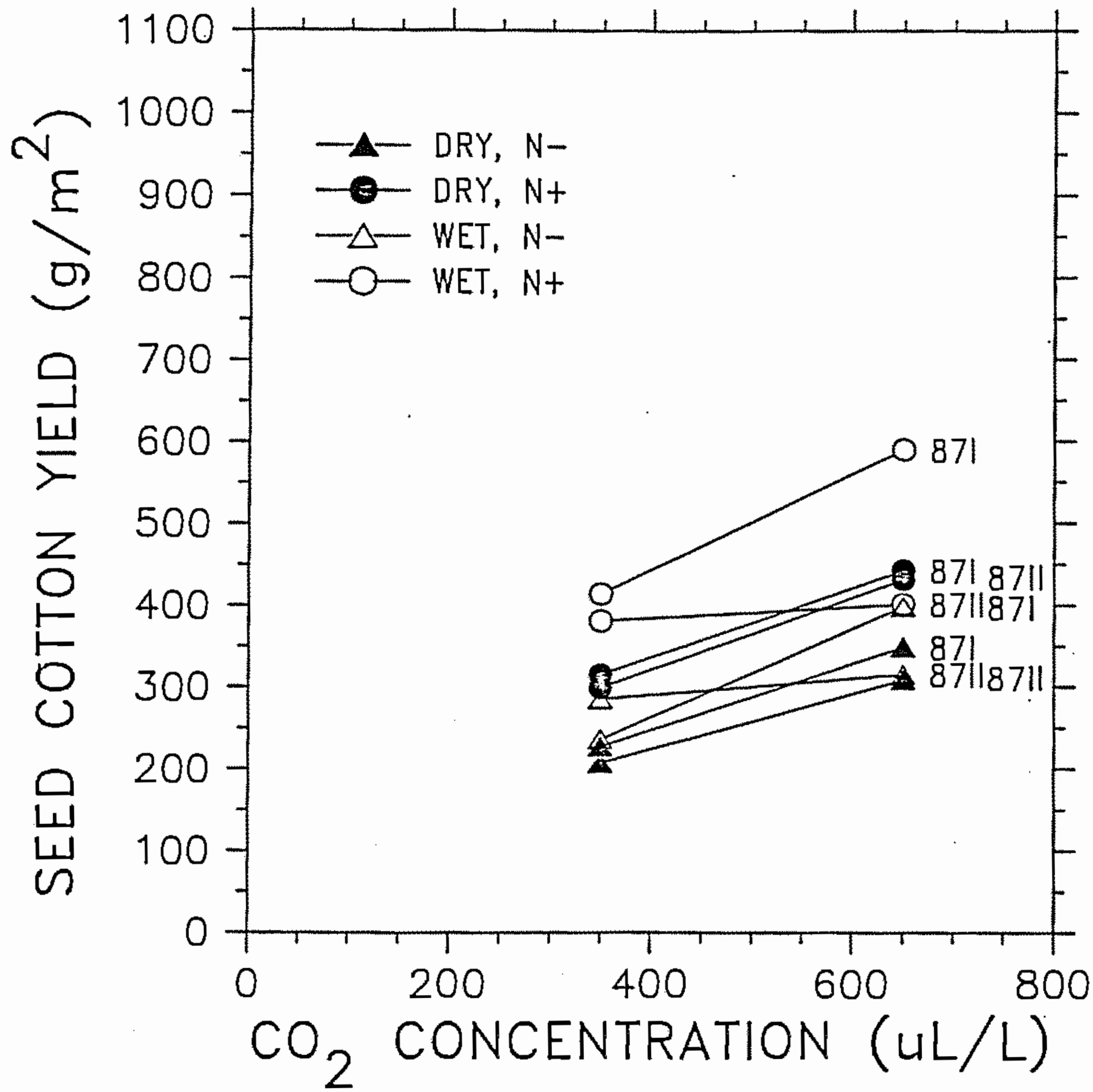

Figure 8. Seed cotton (lint plus seed) yield versus CO_2 concentration for the 1987 CO_2-WATER-NITROGEN experiment. The labels on the right identify the year and replicate of the particular data points.

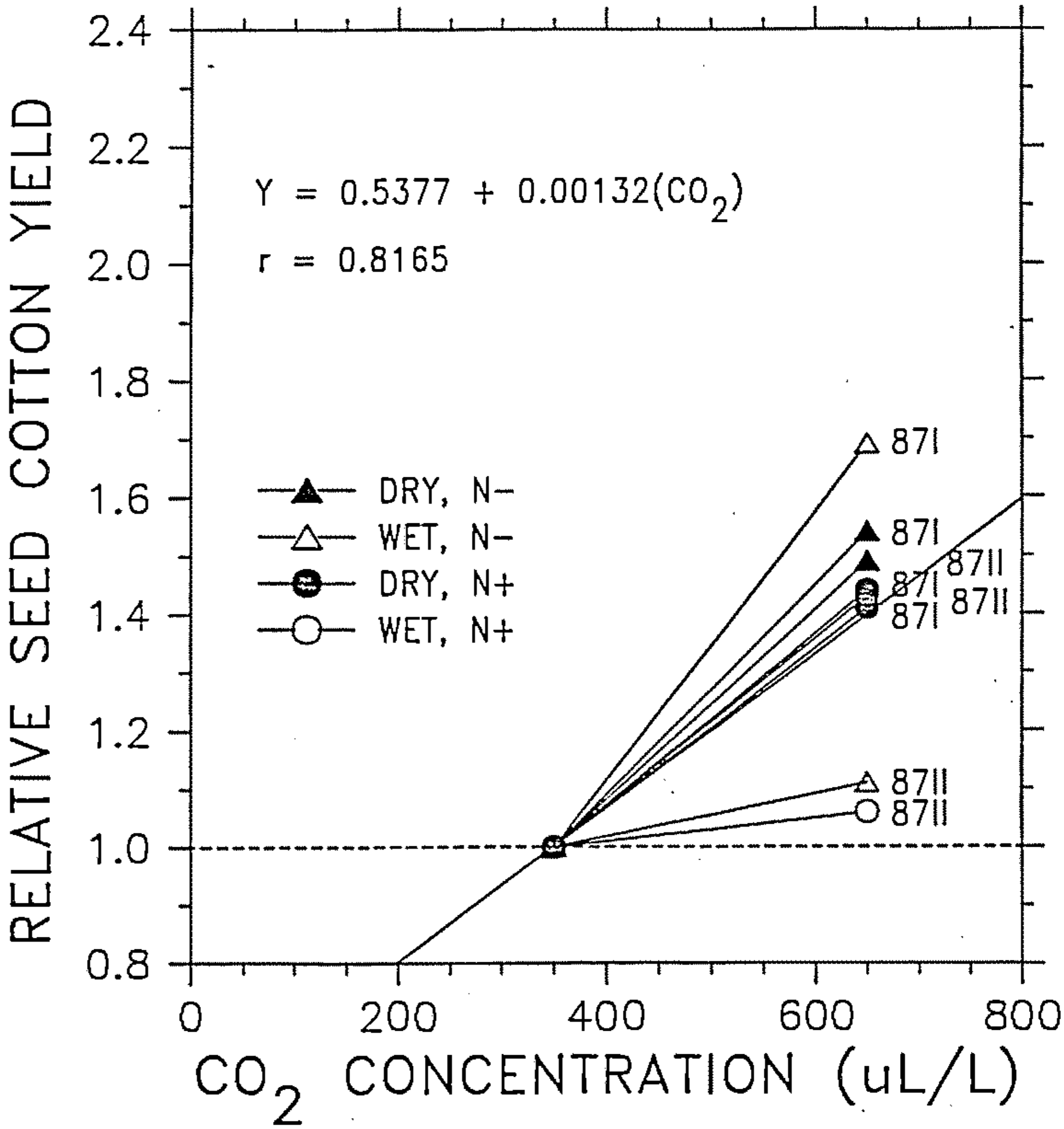

Figure 9. Seed cotton yield relative to the ambient CO_2 chambers versus CO_2 concentration for the 1987 CO_2-WATER-NITROGEN experiment. The labels on the right identify the year and replicate of the particular data points.

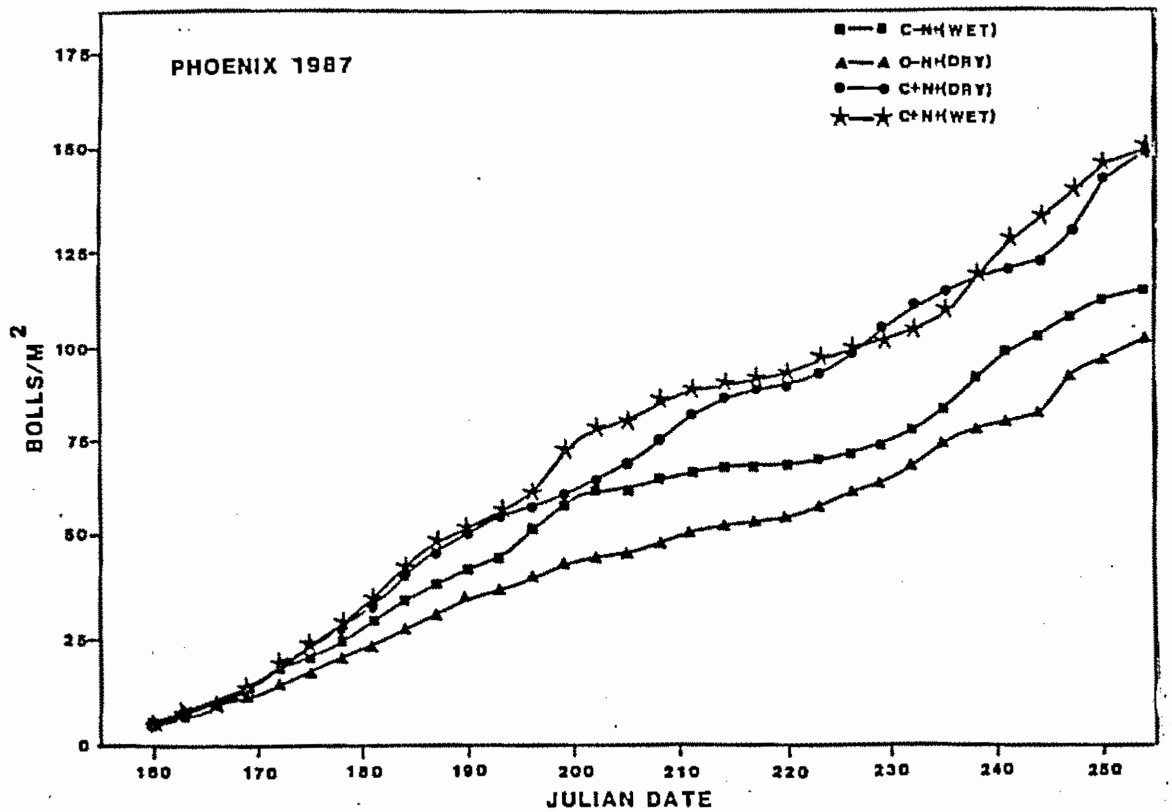

Figure 10. Accumulated number of bolls in the open-top chambers. Data are from both replications of the nitrogen-added (N^+) plots for the wet and dry ambient CO_2 chambers (C^-) and the wet and dry 650 $\mu\ell/\ell$ CO_2 (C^+) treatments.

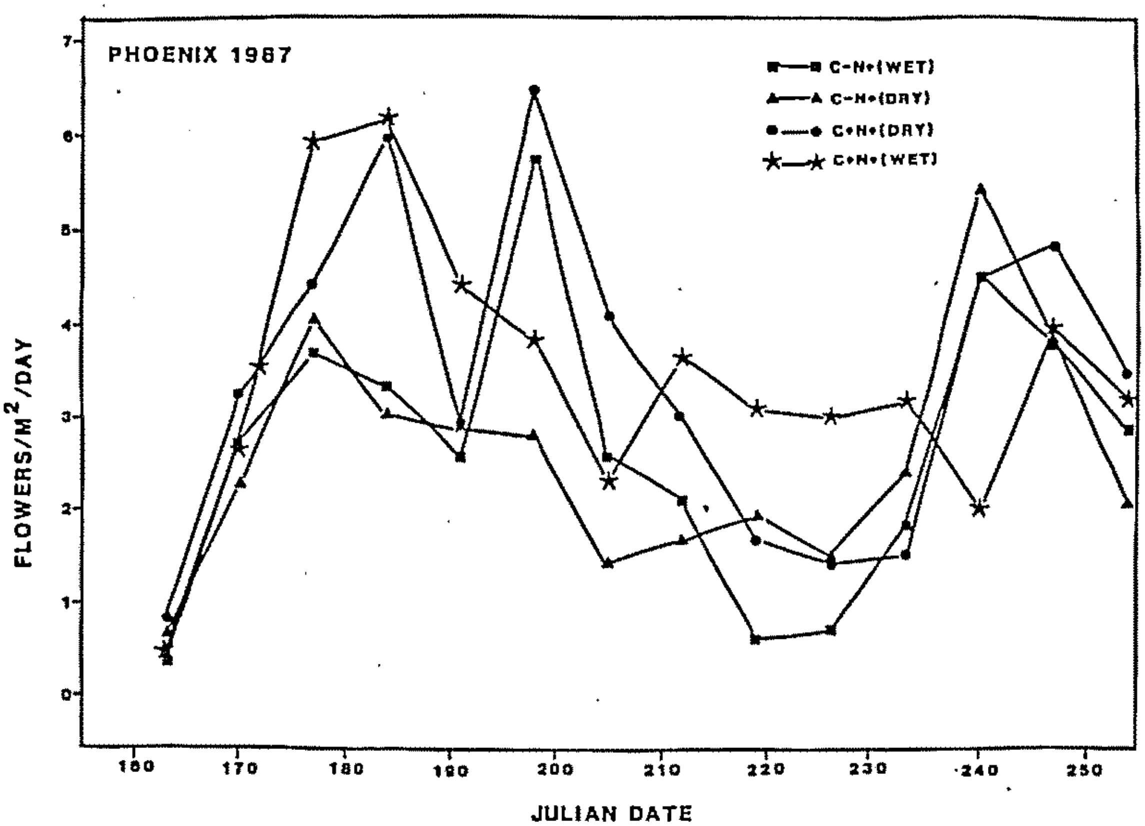

Figure 11. Weekly average rate of flower production in the open-top chambers that received added nitrogen (N^+).

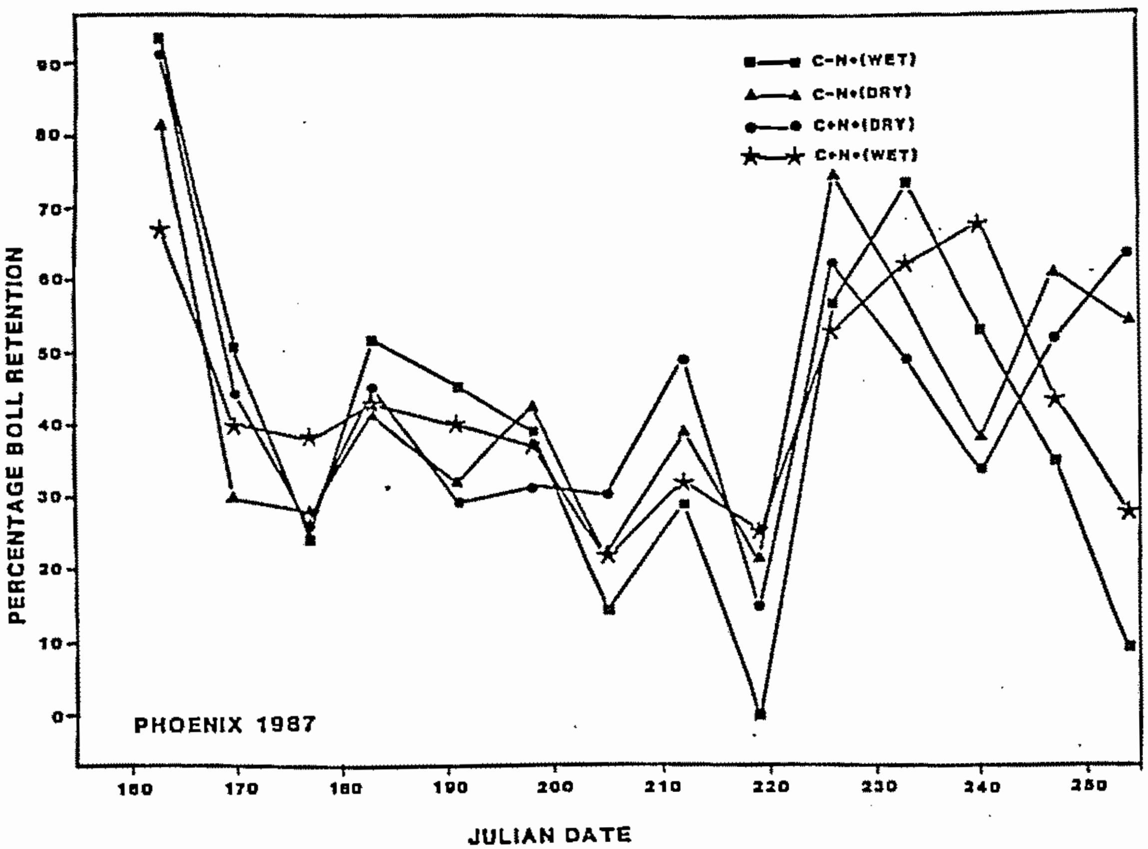

Figure 12. Boll retention in the open-top chambers that received added nitrogen (N^+). The data are the weekly average percentage of blossoms produced which resulted in harvestable bolls.

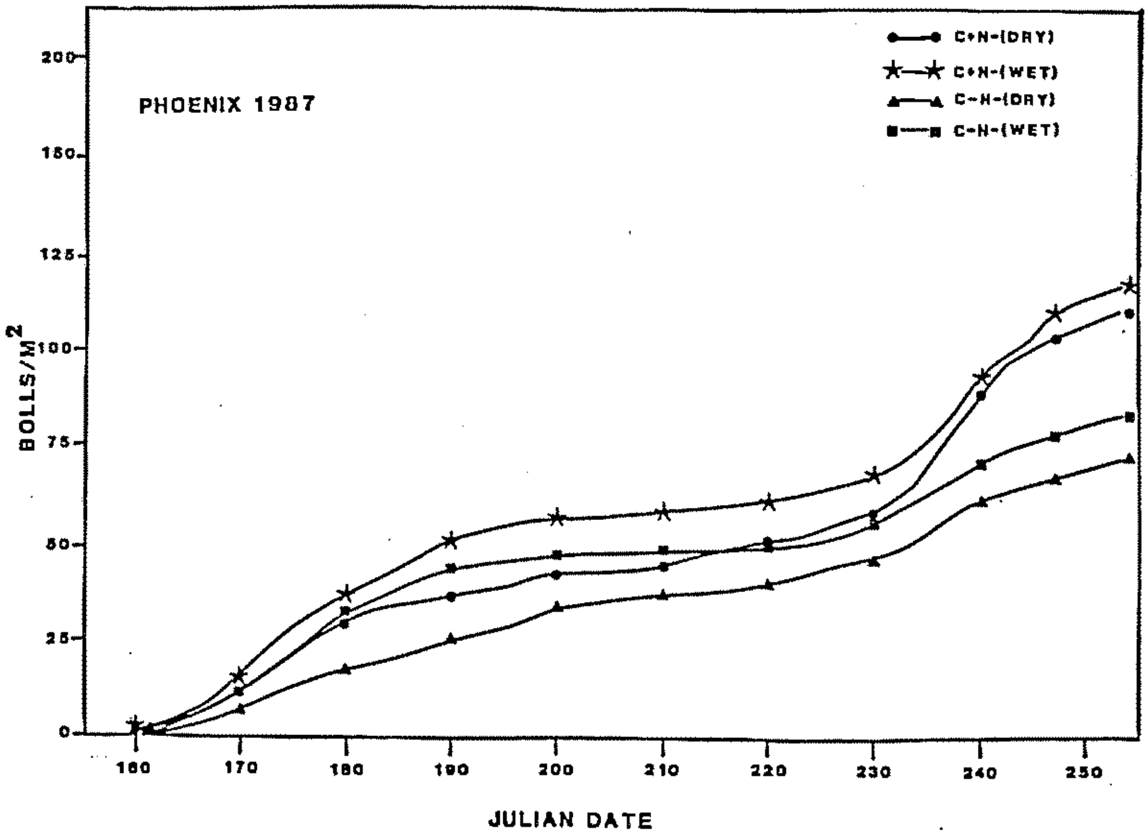

Figure 13. Accumulated number of bolls in the open-top chambers. Data are from both replications of the no-nitrogen-added (N^-) plots for the wet and dry ambient CO_2 chambers (C^-) and the wet and dry 650 $\mu\ell/\ell$ CO_2 (C^+) treatments.

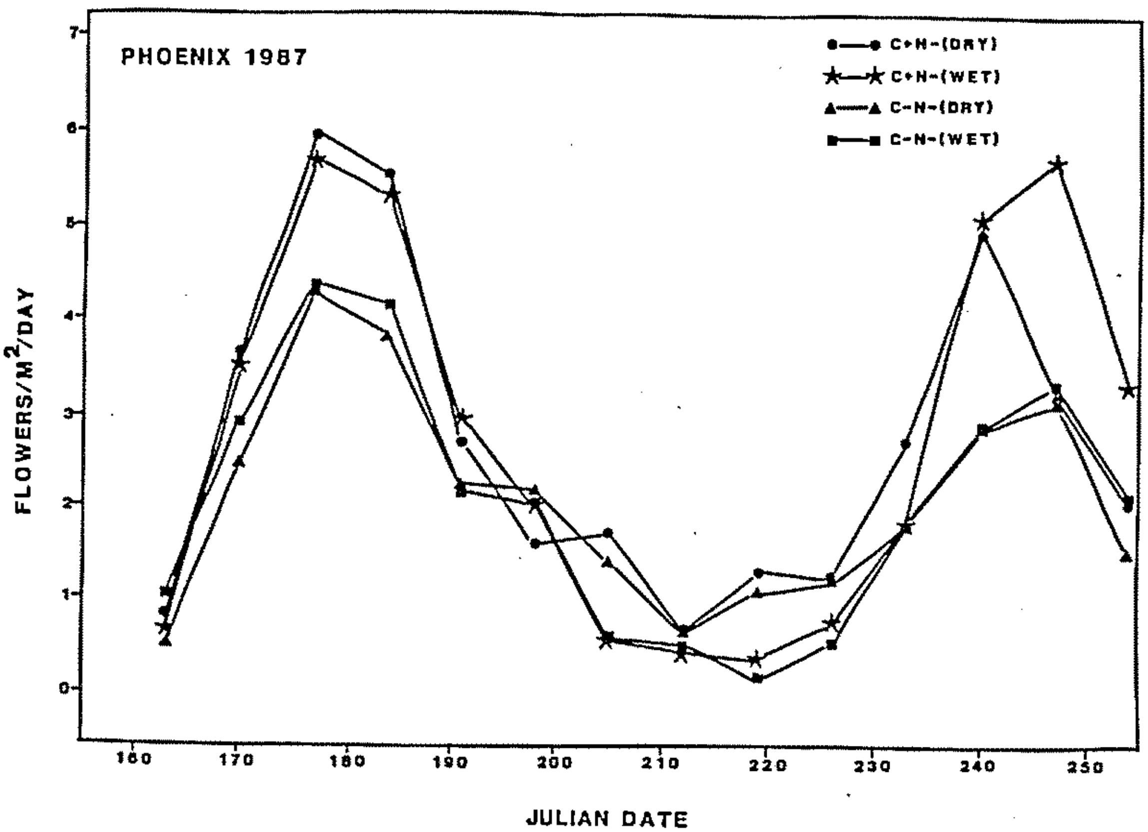

Figure 14. Weekly average rate of flower production in the open-top chambers that received no added nitrogen (N^-).

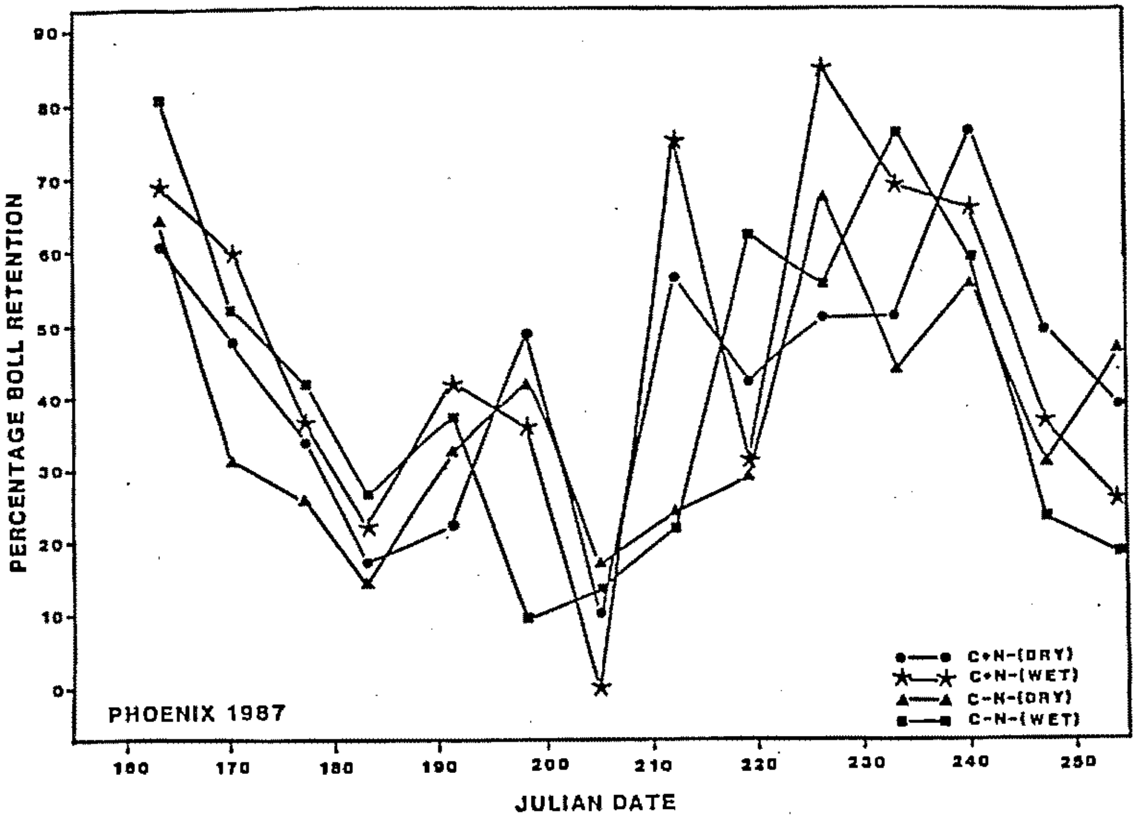

Figure 15. Boll retention in the open-top chambers that received no added nitrogen (N$^-$). The data are the weekly average percentage of blossoms produced which resulted in harvestable bolls.

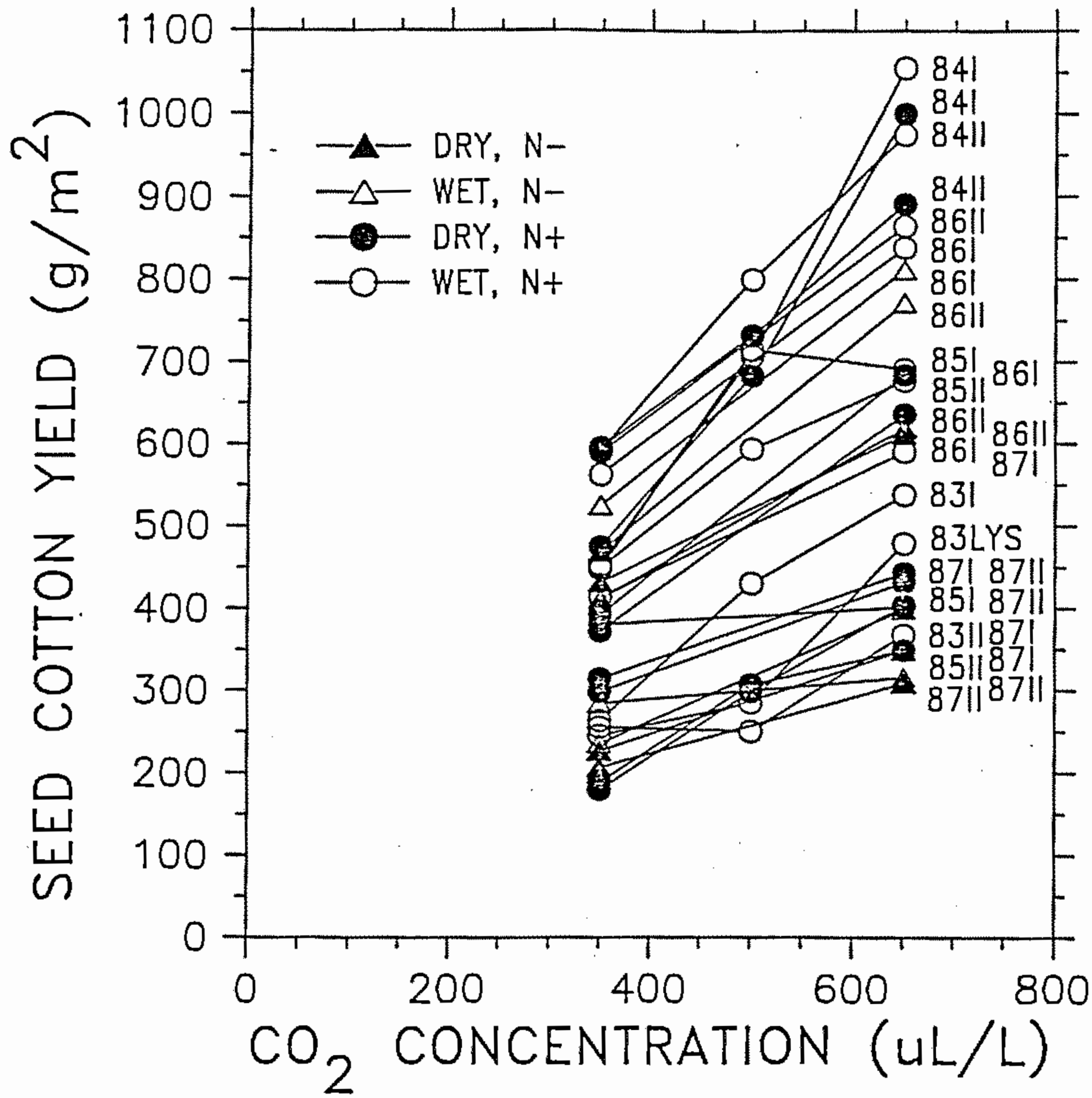

Figure 16. Seed cotton yield versus CO_2 concentration for 5 years' worth of experiments with open-top chambers at Phoenix, AZ. The labels on the right identify the year and replicate of the particular data points.

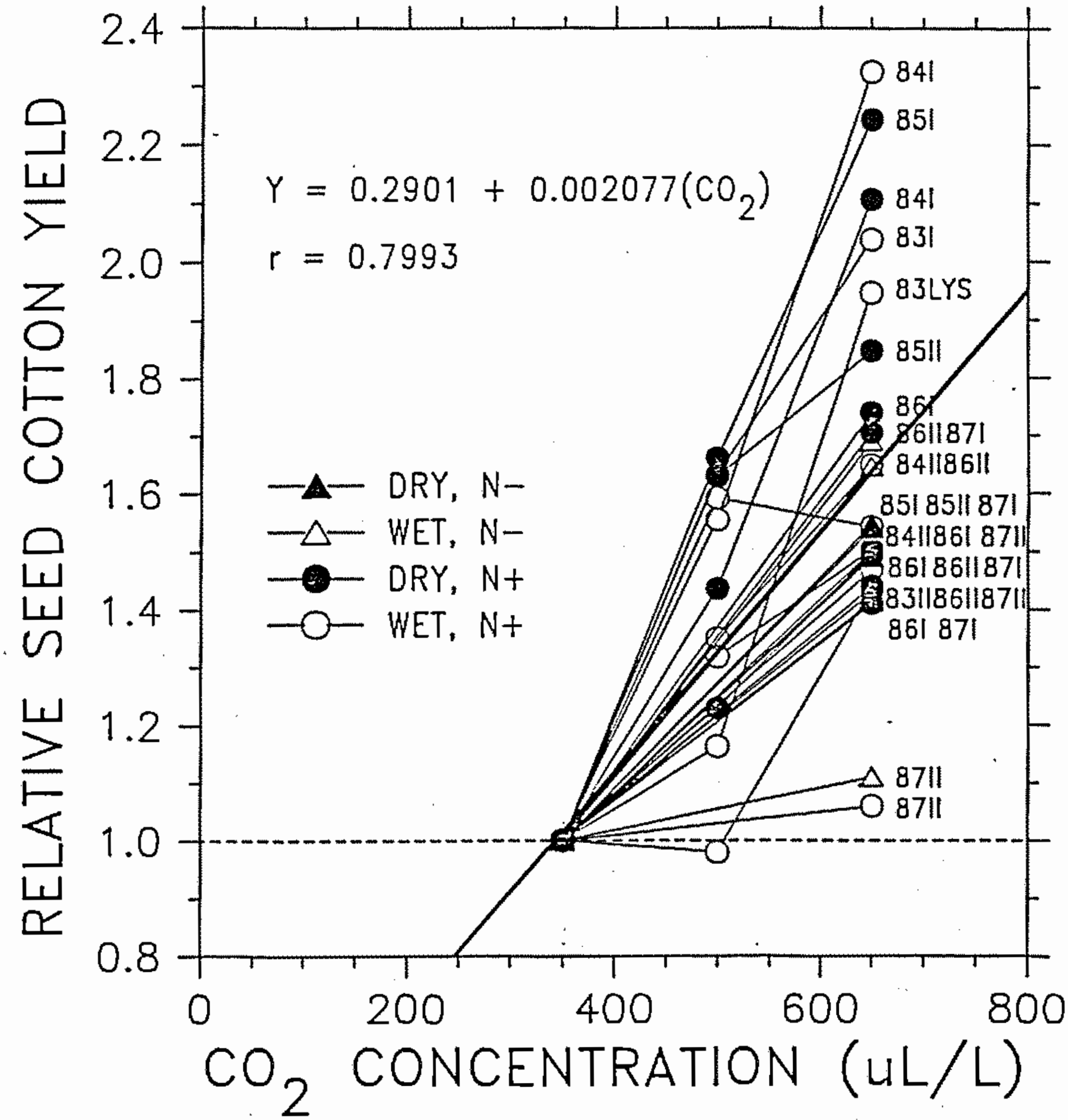

Figure 17. Seed cotton yield relative to the ambient CO_2 chambers versus CO_2 concentration for 5 years' worth of experiments with open-top chambers at Phoenix, AZ. The labels on the right identify the year and replicate of the particular data points.

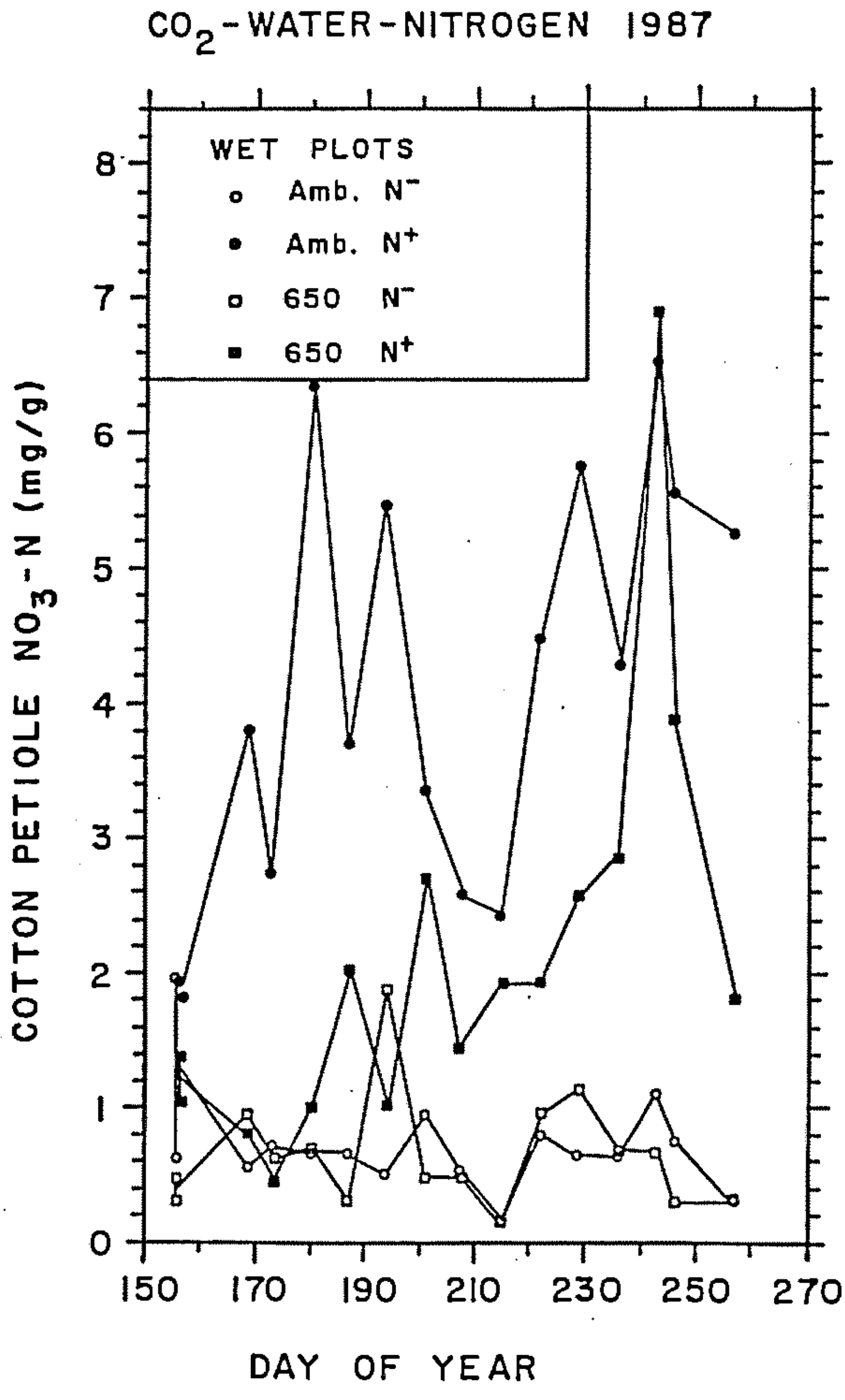

Figure 18. Petiole NO_3^- nitrogen contents versus day of the year for the ambient CO_2 - low N, ambient CO_2 - high N, 650 $\mu\ell/\ell$ CO_2 - low N, and 650 $\mu\ell/\ell$ CO_2 - high N treatments, all from the wet plots.

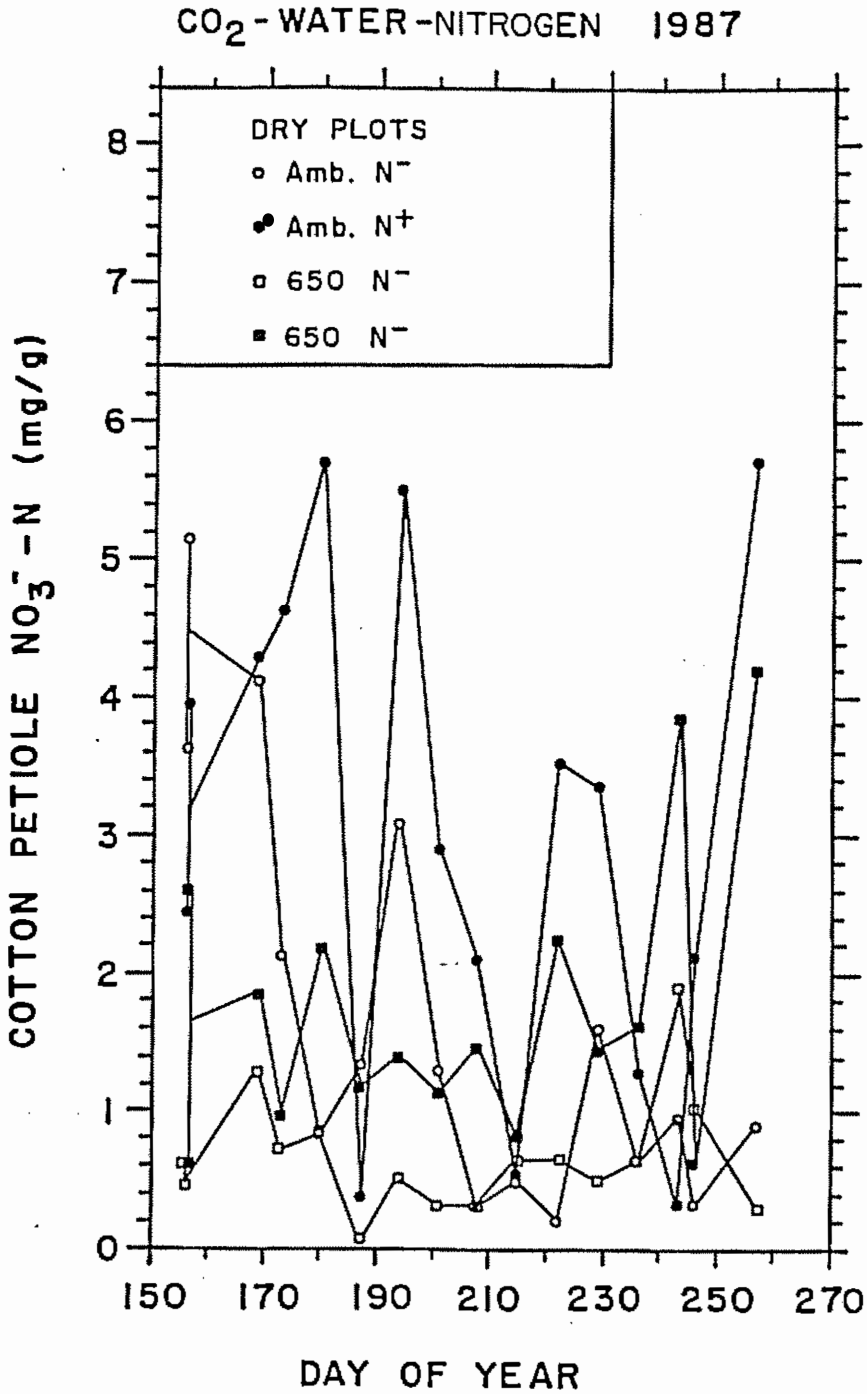

Figure 19. Petiole NO_3^- nitrogen contents versus day of the year for the ambient CO_2 - low N, ambient CO_2 - high N, 650 $\mu\ell/\ell$ CO_2 - low N, and 650 $\mu\ell/\ell$ CO_2 - high N treatments, all from the dry plots.

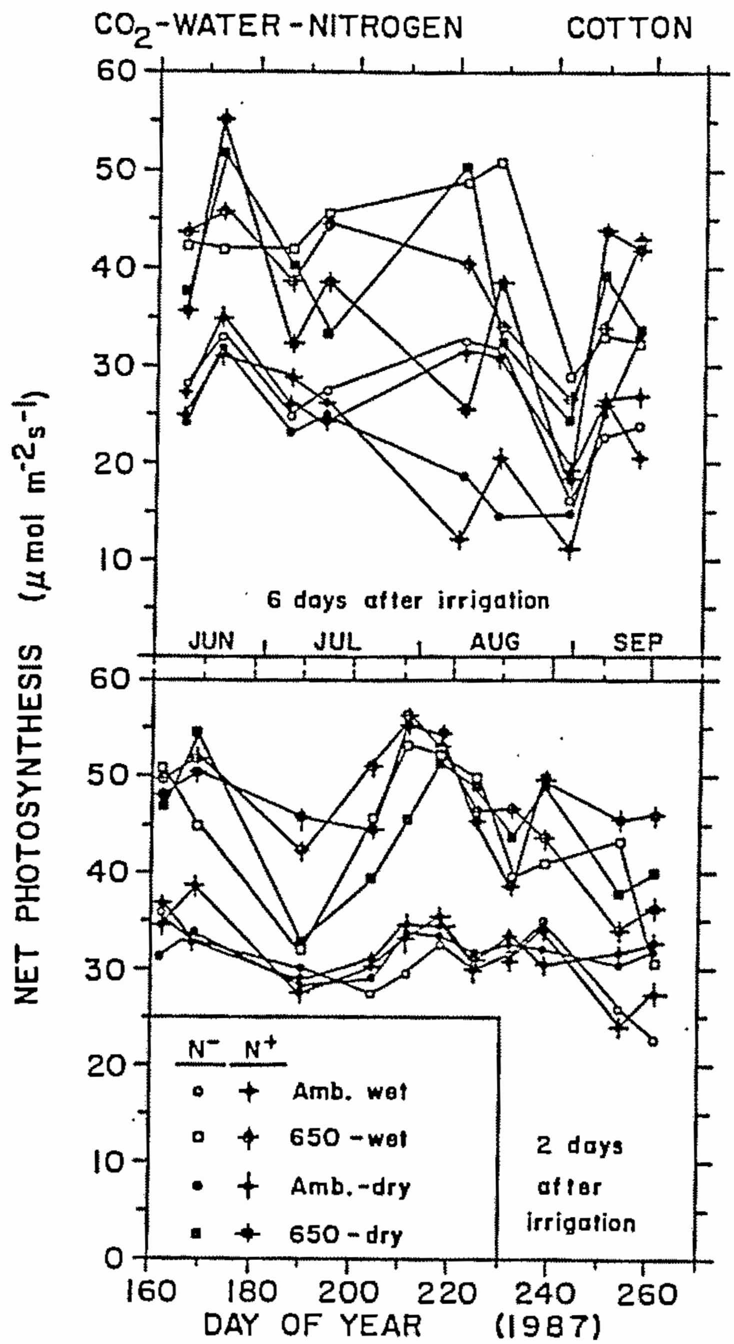

Figure 20. Net photosynthesis of cotton leaves versus day of year (1987) for the CO_2-WATER-NITROGEN experiment measured 6 days (upper graph) and 2 days (lower graph) after irrigation. Each data point is an average over three leaves per chamber, 2 reps, and 2 nitrogen treatments.

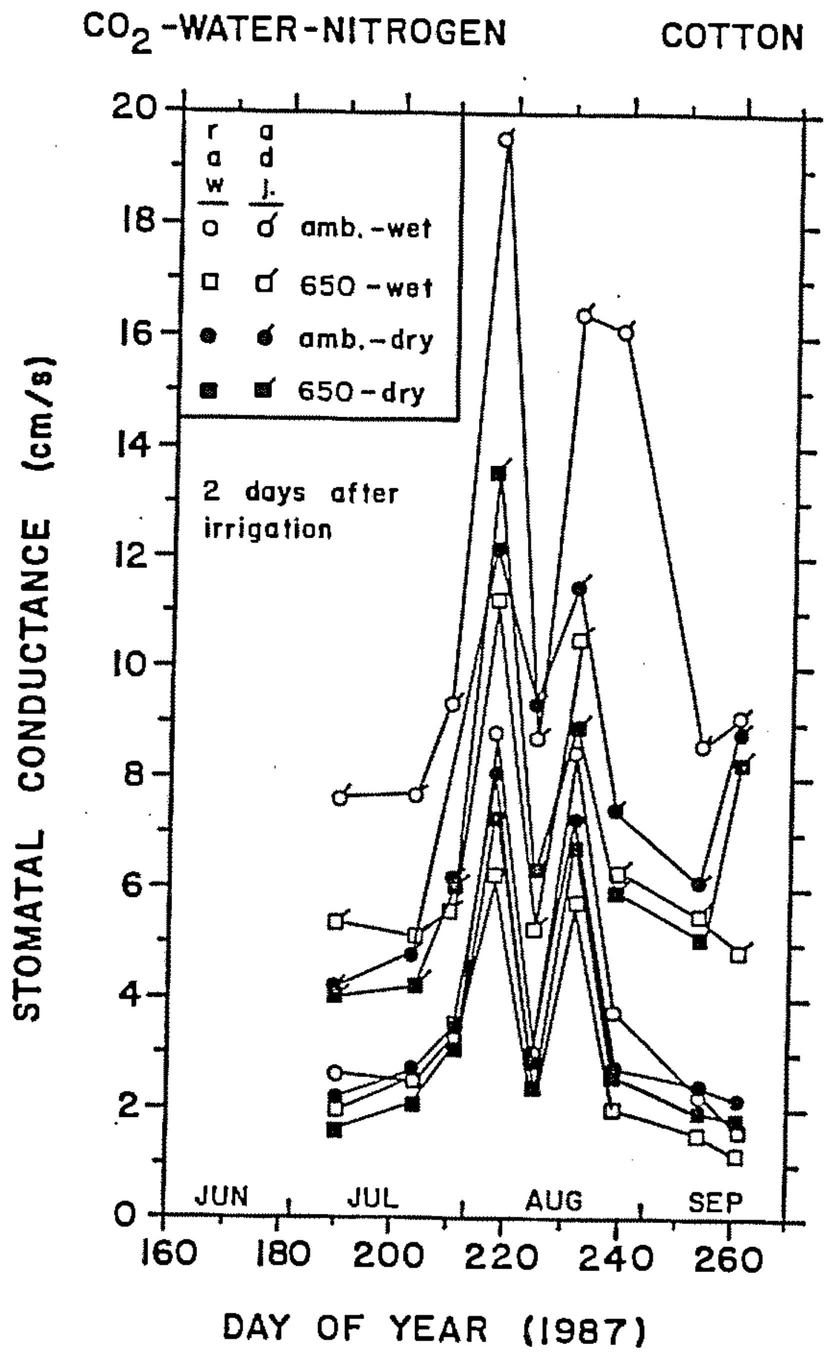

Figure 21. Stomatal conductance of cotton leaves versus day of year (1987) for the CO_2-WATER-NITROGEN experiment measured 2 days after irrigation. Each point is an average over 3 leaves per chamber, 2 reps, and 2 nitrogen treatments. Both "raw" conductance values and also "adjusted" values are plotted, where the adjustment was accomplished following the recommended procedure of Idso et al. (1987).

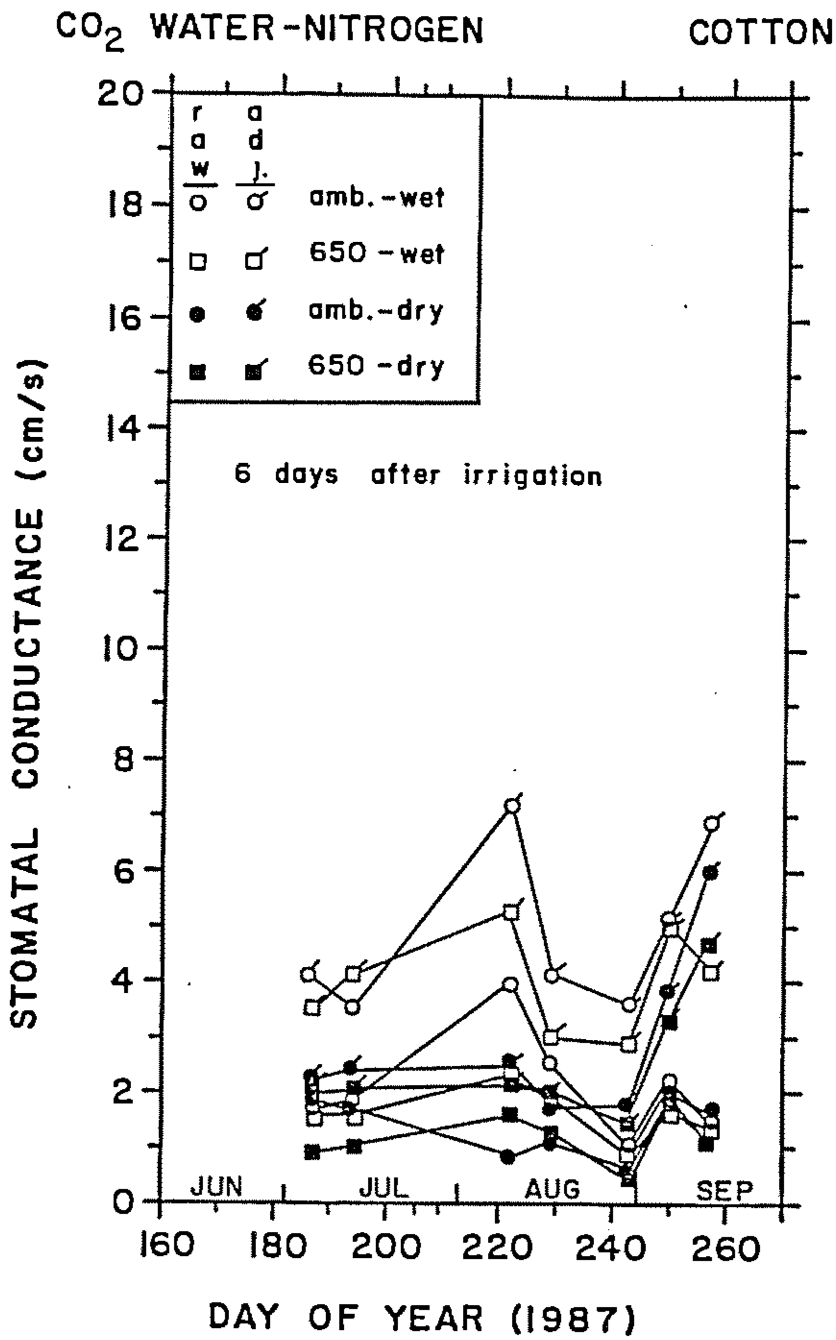

Figure 22. Stomatal conductance of cotton leaves versus day of year (1987) for the CO_2-WATER-NITROGEN experiment measured 6 days after irrigation. Each point is an average over 3 leaves per chamber, 2 reps, and 2 nitrogen treatments. Both "raw" conductance values and also "adjusted" values are plotted, where the adjustment was accomplished following the recommended procedure of Idso et al. (1987).

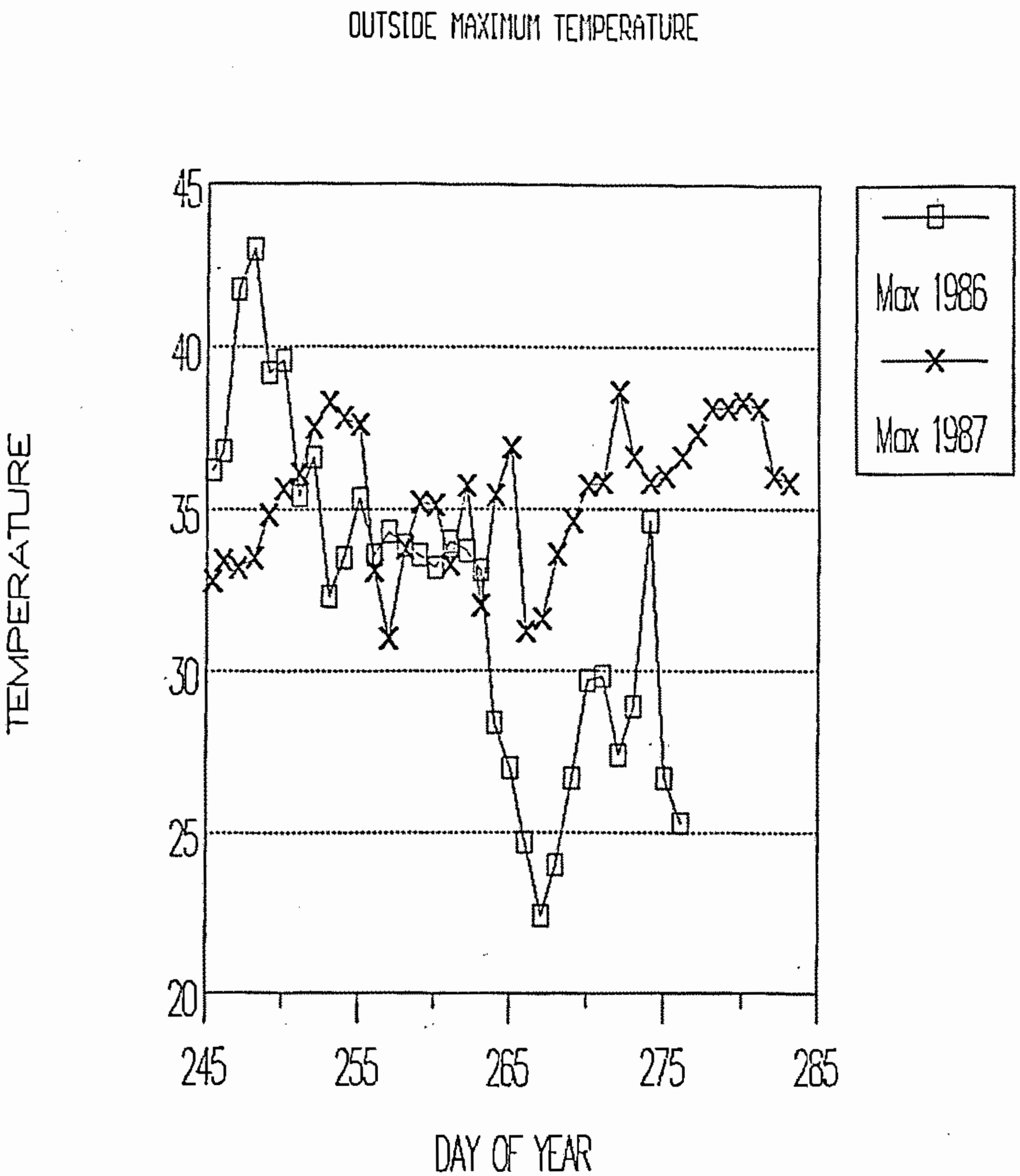

Figure 23. Maximum daily temperatures from day of year 245 (2 September) through 285 (12 October) for 1986 and 1987.

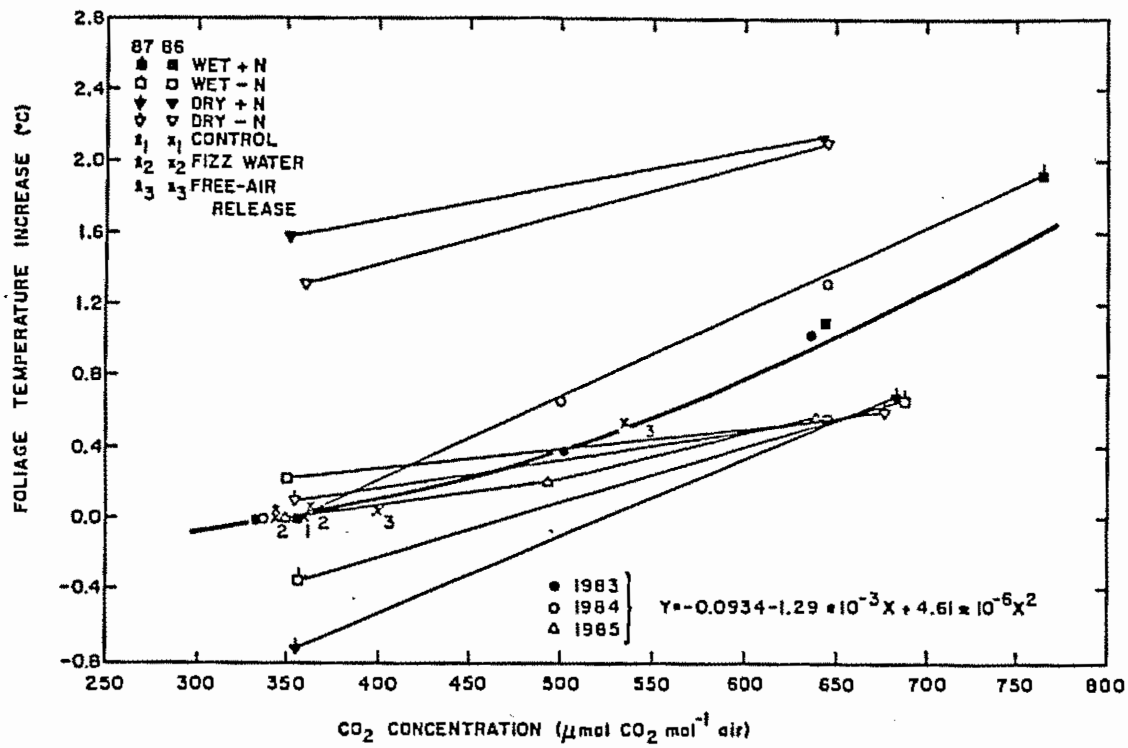

Figure 24. Cotton foliage temperature increase caused by atmospheric CO_2 enrichment (with respect to the ambient control plots). The curve is the regression fit to the data from 1983-85 (Kimball et al., 1985). Each symbol is an average over 20 observations per plot per day, several clear days each year, and 2 or 4 replicate plots.

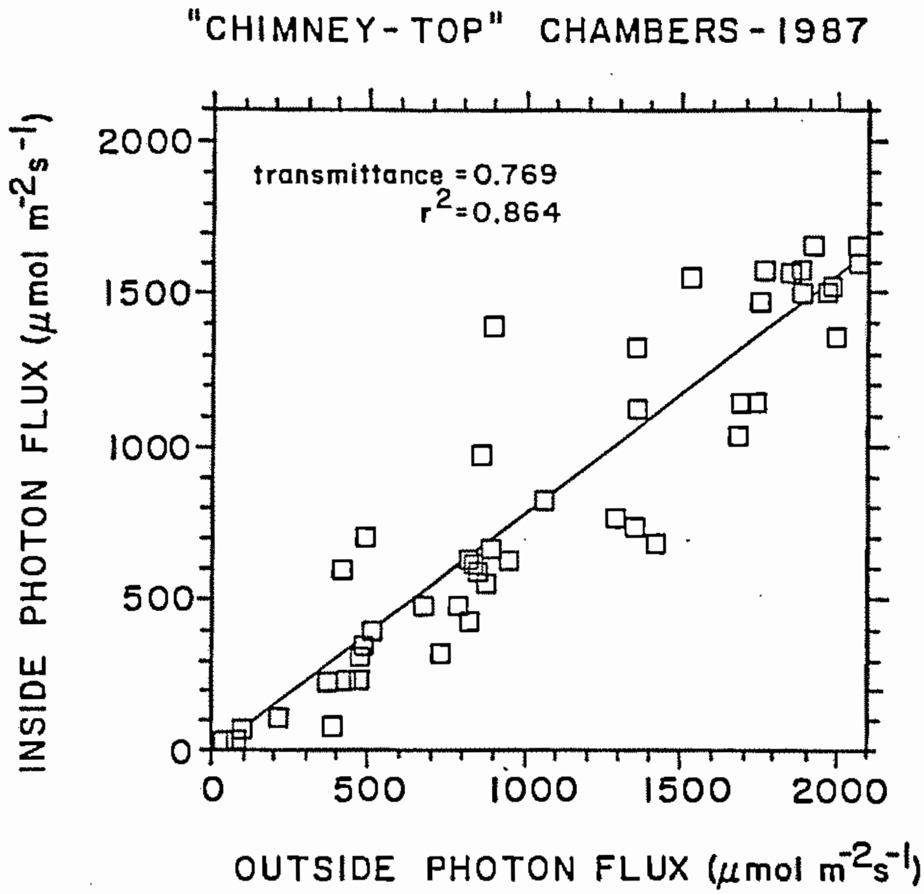

Figure 25. Photosynthetic photon flux (PPF) inside and outside "chimney-top" chambers, as measured on 3, 9, 10, and 11 September 1987. Also shown is the mean transmittance as determined by the slope of the least-squares line through the origin.

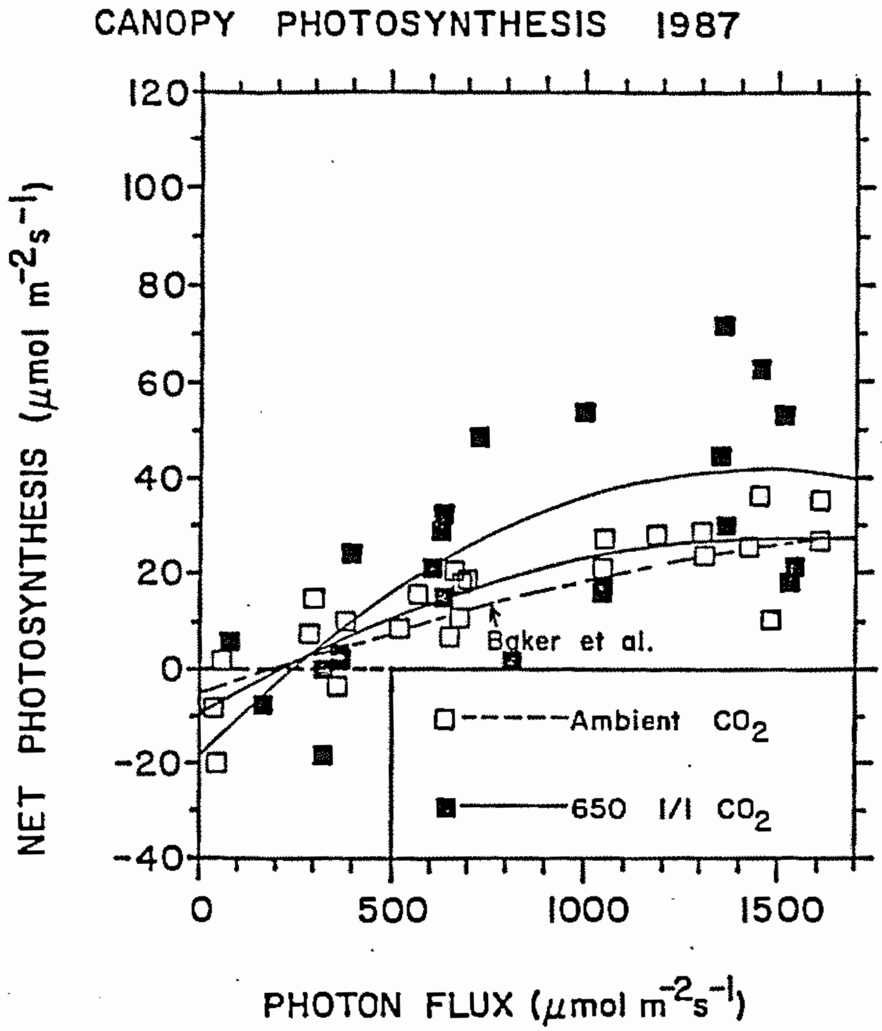

Figure 26. Cotton canopy net photosynthesis measured with "chimney-top" chambers vs. photosynthetic photon flux measured by outside pyranometer times a transmittance of 0.769 for chambers at both ambient and 650 $\mu\ell/\ell$ of CO_2. Also shown is a curve from Baker et al. (1972) which was used to develop the net photosynthesis subroutine in GOSSYM by Baker et al. (1983) for a temperature of 30°C and a vapor pressure deficit of 1 kPa.

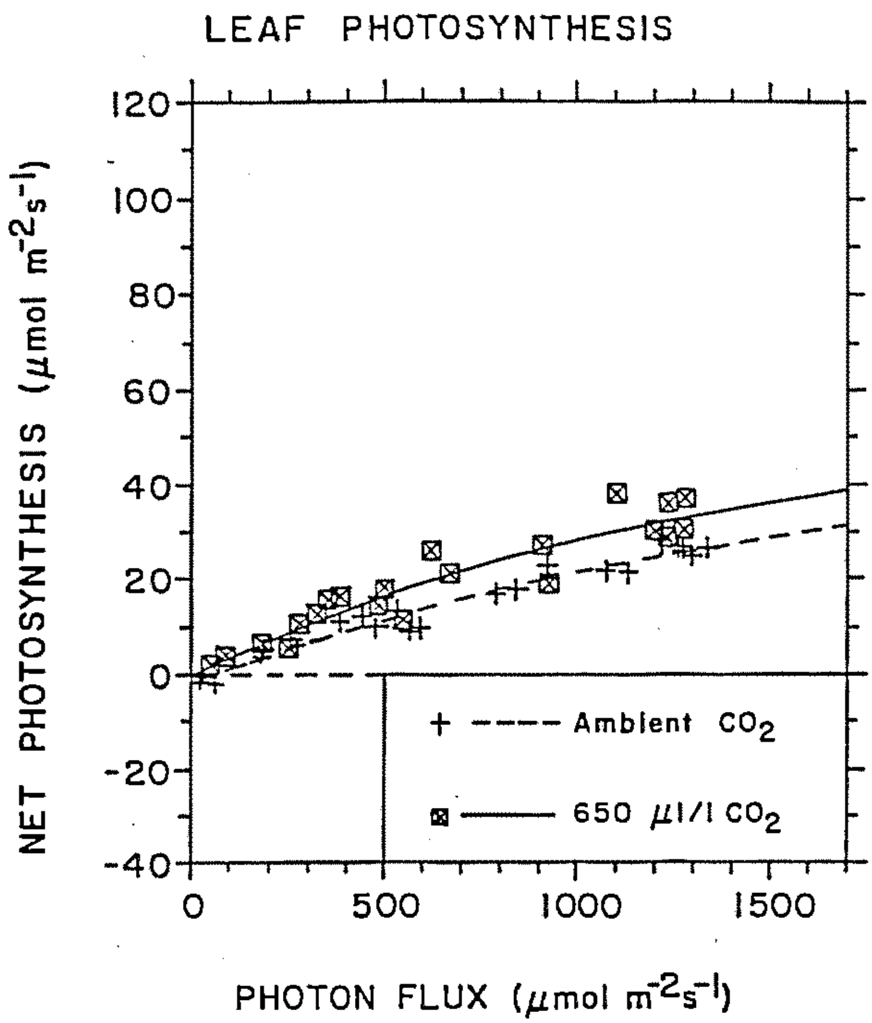

Figure 27. Mean cotton leaf net photosynthesis (10 observations per point) measured with a Li-Cor 6200 Portable Photosynthesis System inside "chimney-top" chambers at ambient and 650 $\mu\ell/\ell$ of CO_2 versus the corresponding mean photosynthetic photon flux inside the leaf chamber on 3, 9, 10, and 11 September 1987.

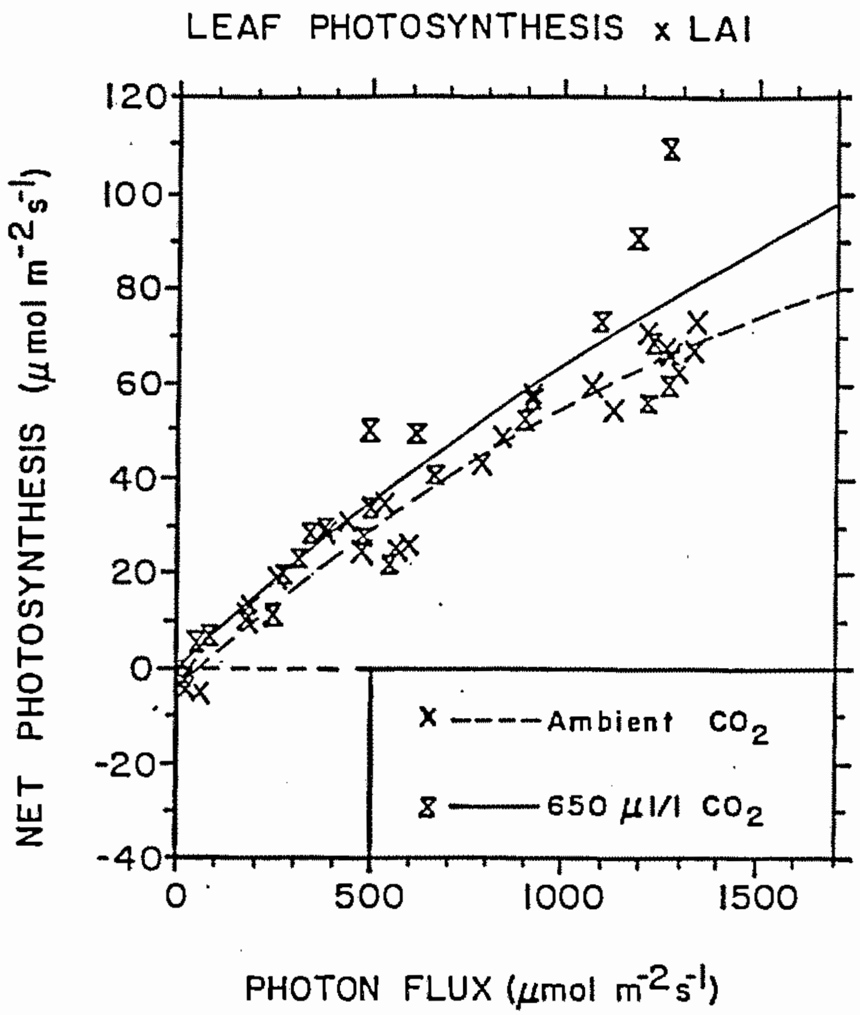

Figure 28. Same as Figure 27 except the leaf photosynthesis values have been multiplied by the leaf area index (LAI) of the cotton canopy in the particular chamber.

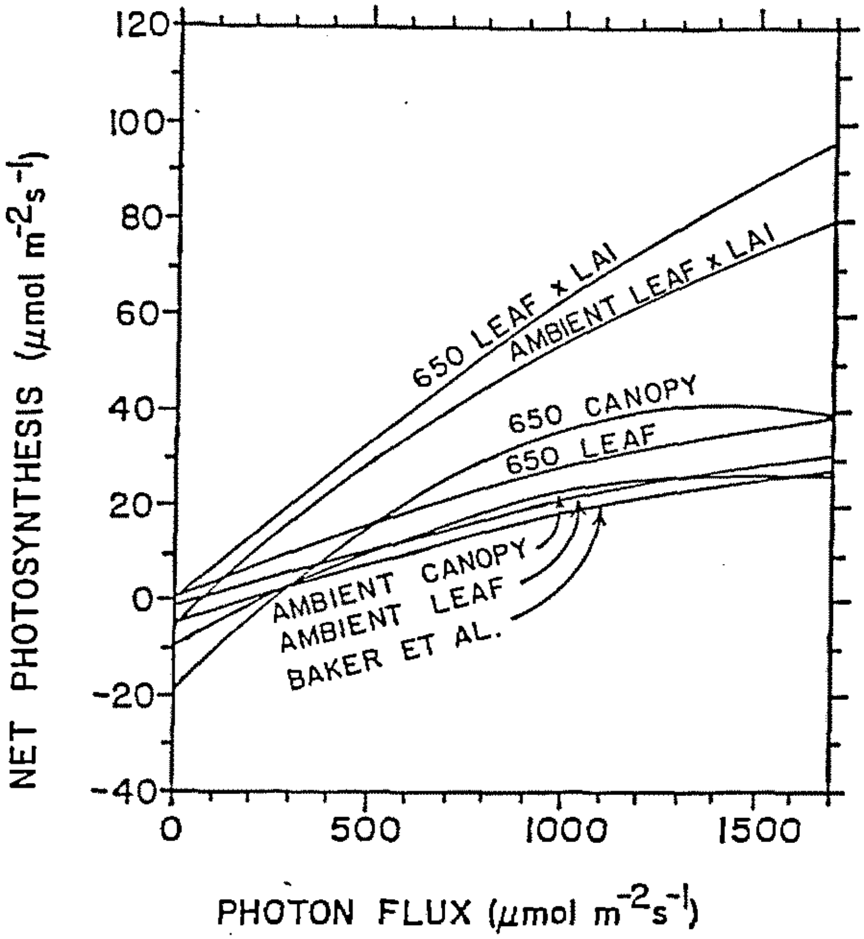

Figure 29. The regression curves of net cotton canopy photosynthesis, leaf photosynthesis, and leaf photosynthesis times LAI on photosynthetic photon flux from Figures 26, 27, and 28. Also shown is a curve from Baker et al. (1972) which was used to develop the net photosynthesis subroutine in GOSSYM by Baker et al. (1983) for a temperature of 30°C and a vapor pressure deficit of 1 kPa.

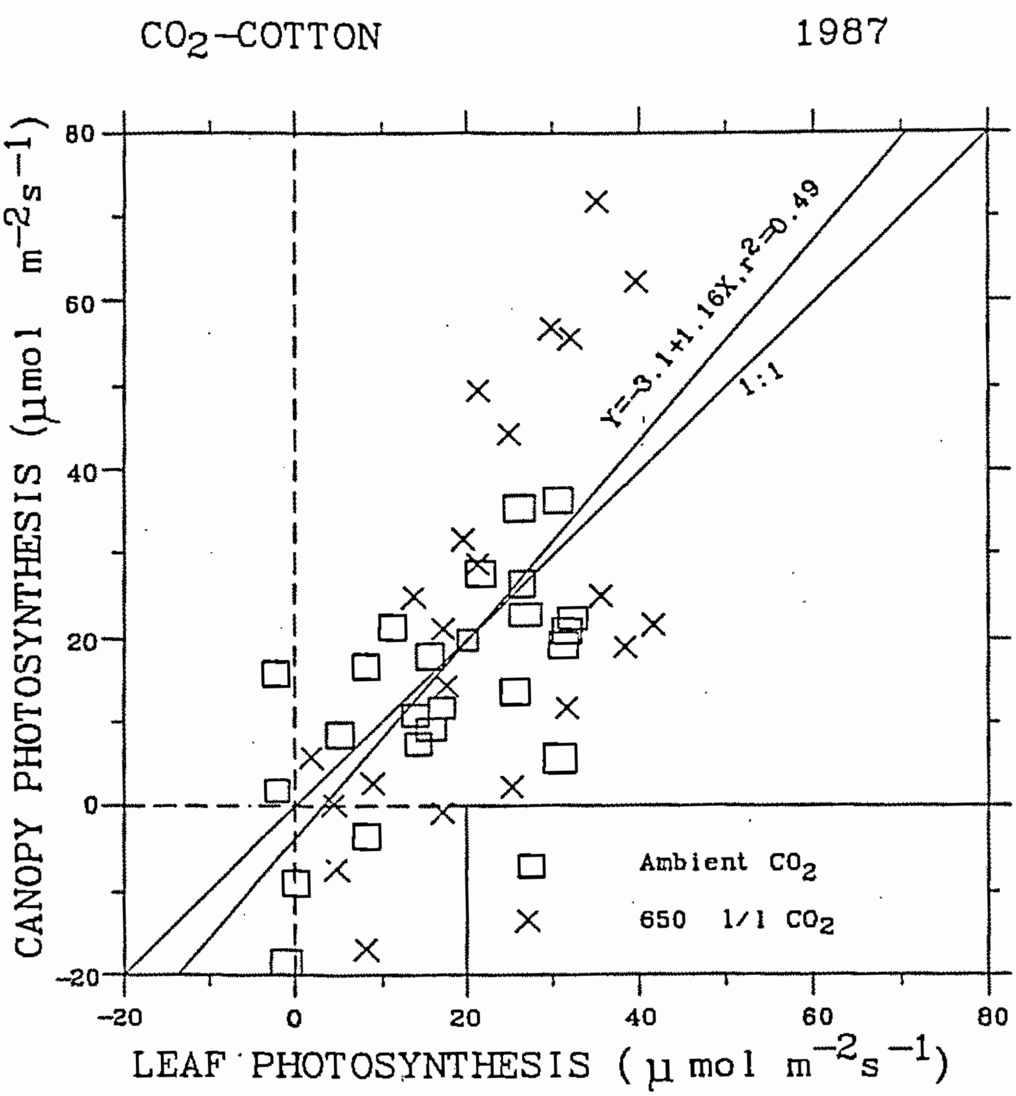

Figure 30. Canopy photosynthesis measured with the "chimney-top" chambers versus leaf photosynthesis measured during the same hour with a Li-Cor portable photosynthesis system. The leaf data are the average of 10 young fully-expanded leaves at the top of the canopy and adjusted for a cuvette transmittance of 0.81 using the photon flux equations for leaves given in Table 15.

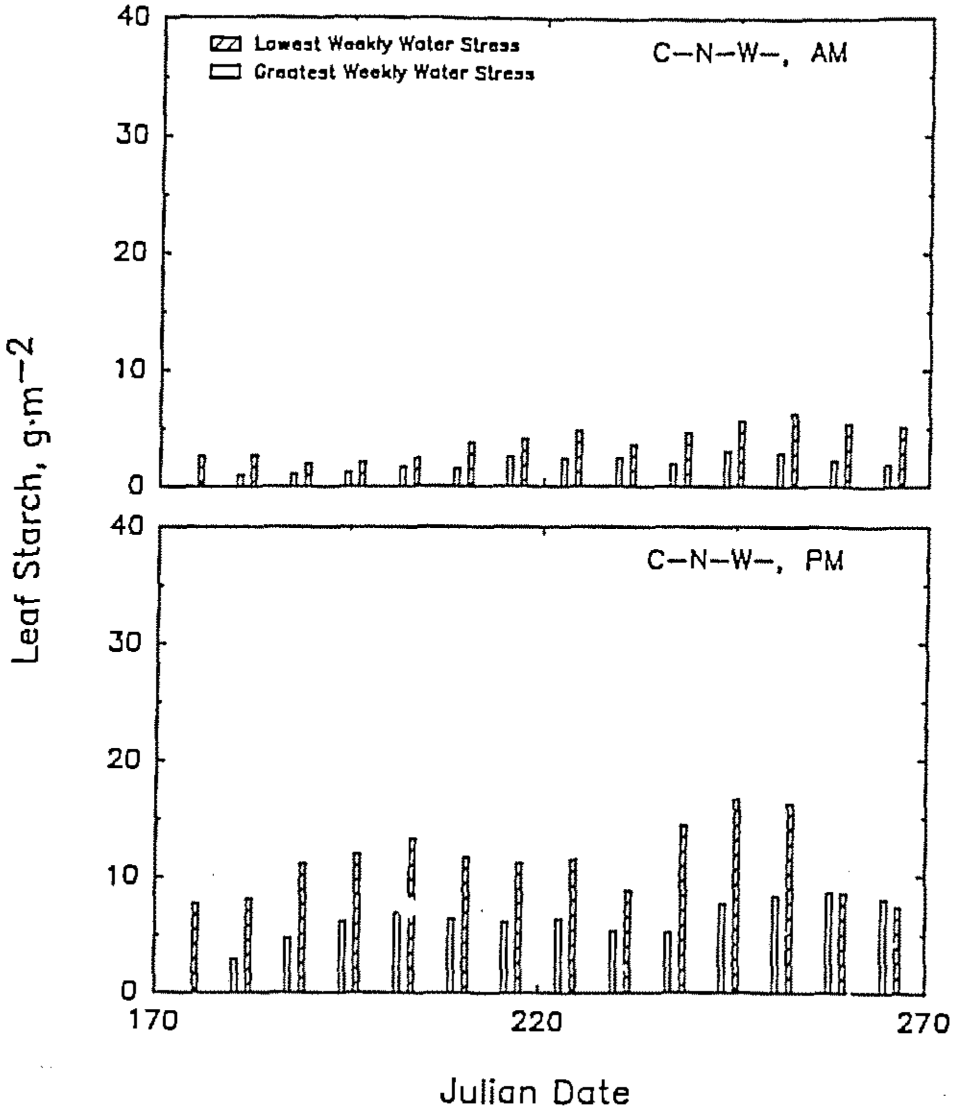

Figure 31. Leaf starch content of chamber-grown cotton plants grown with ambient CO_2 (C-), no added nitrogen (N-), and water-stress (W-). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

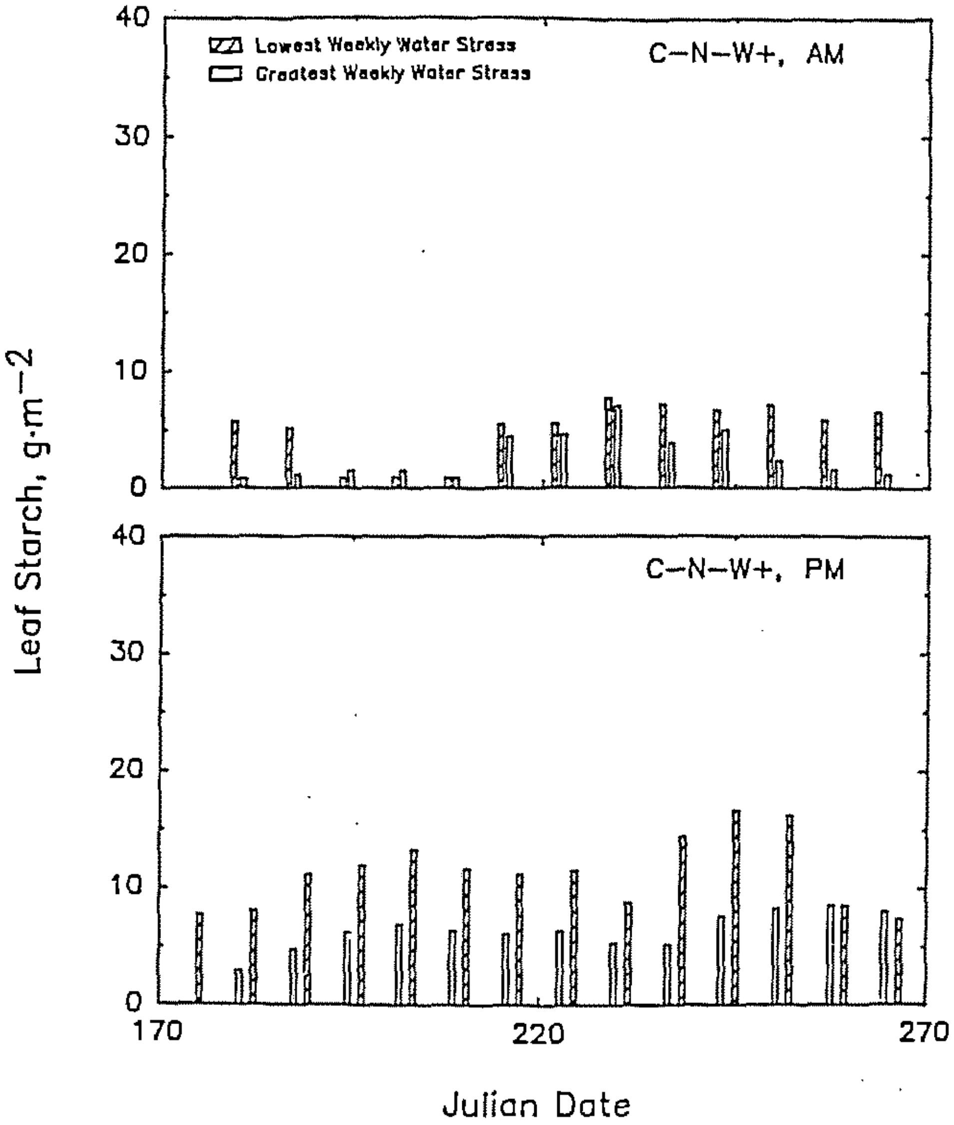

Figure 32. Leaf starch content of chamber-grown cotton plants grown with ambient CO_2 (C-), no added nitrogen (N-), and were well-watered (W+). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

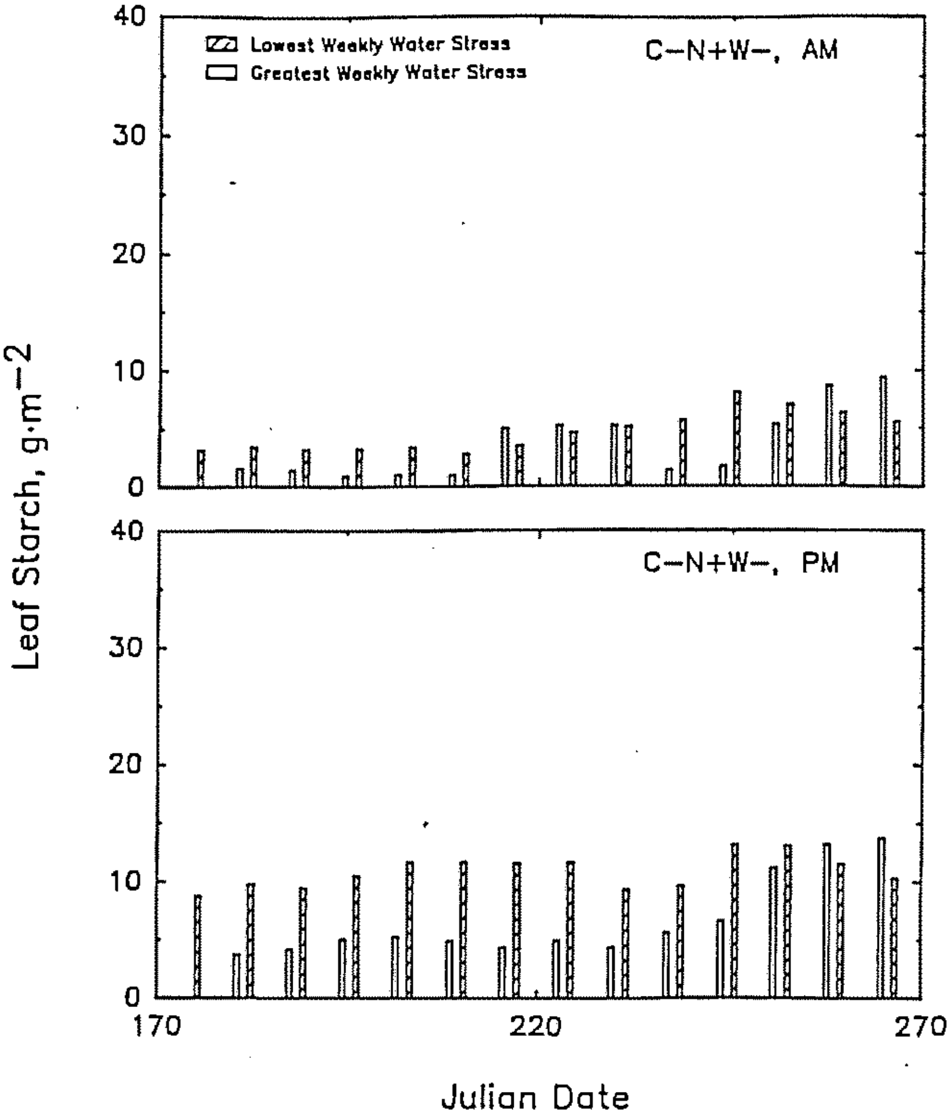

Figure 33. Leaf starch content of chamber-grown cotton plants grown with ambient CO_2 (C-), added nitrogen (N+), and water-stress (W-). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

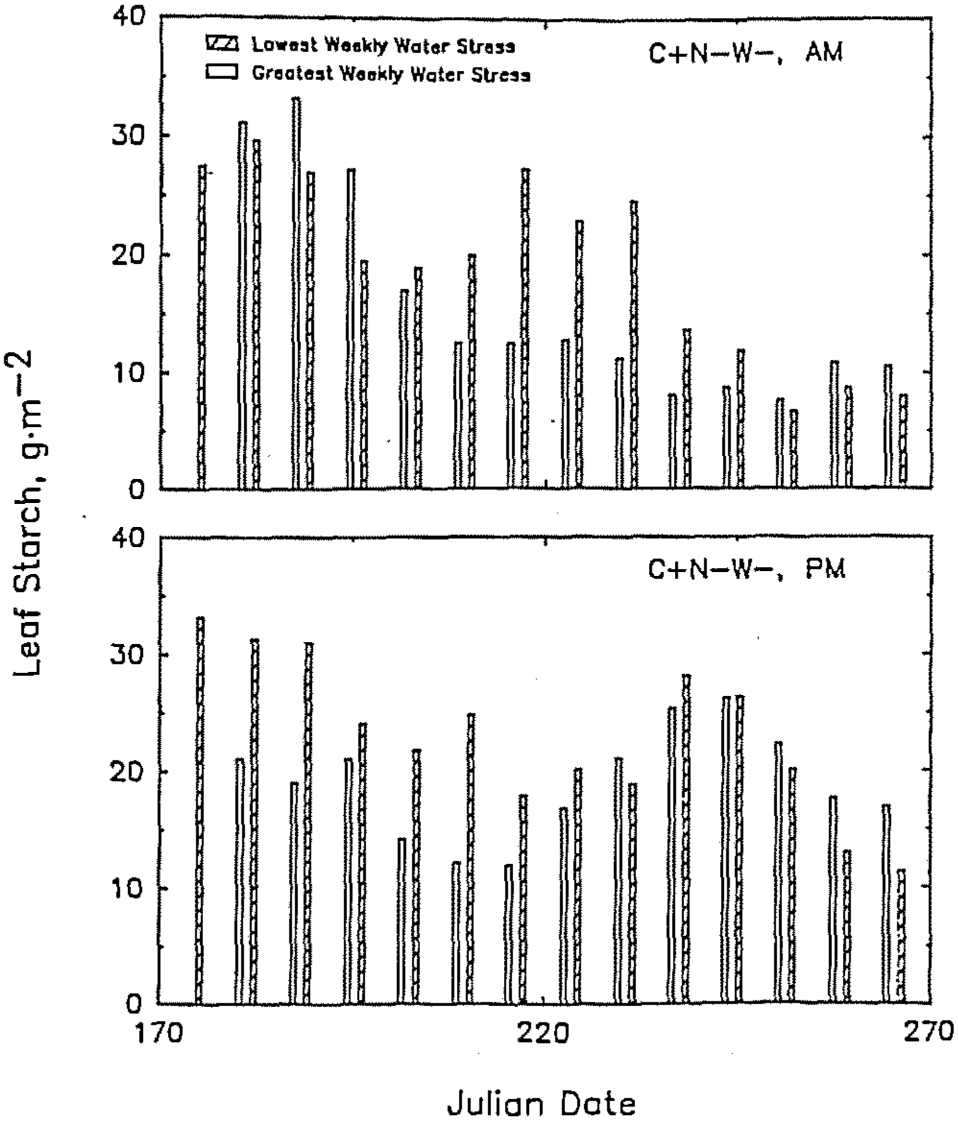

Figure 34. Leaf starch content of chamber-grown cotton plants grown with 650 $\mu\ell/\ell$ CO_2 (C+), no added nitrogen (N-), and water-stress (W-). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

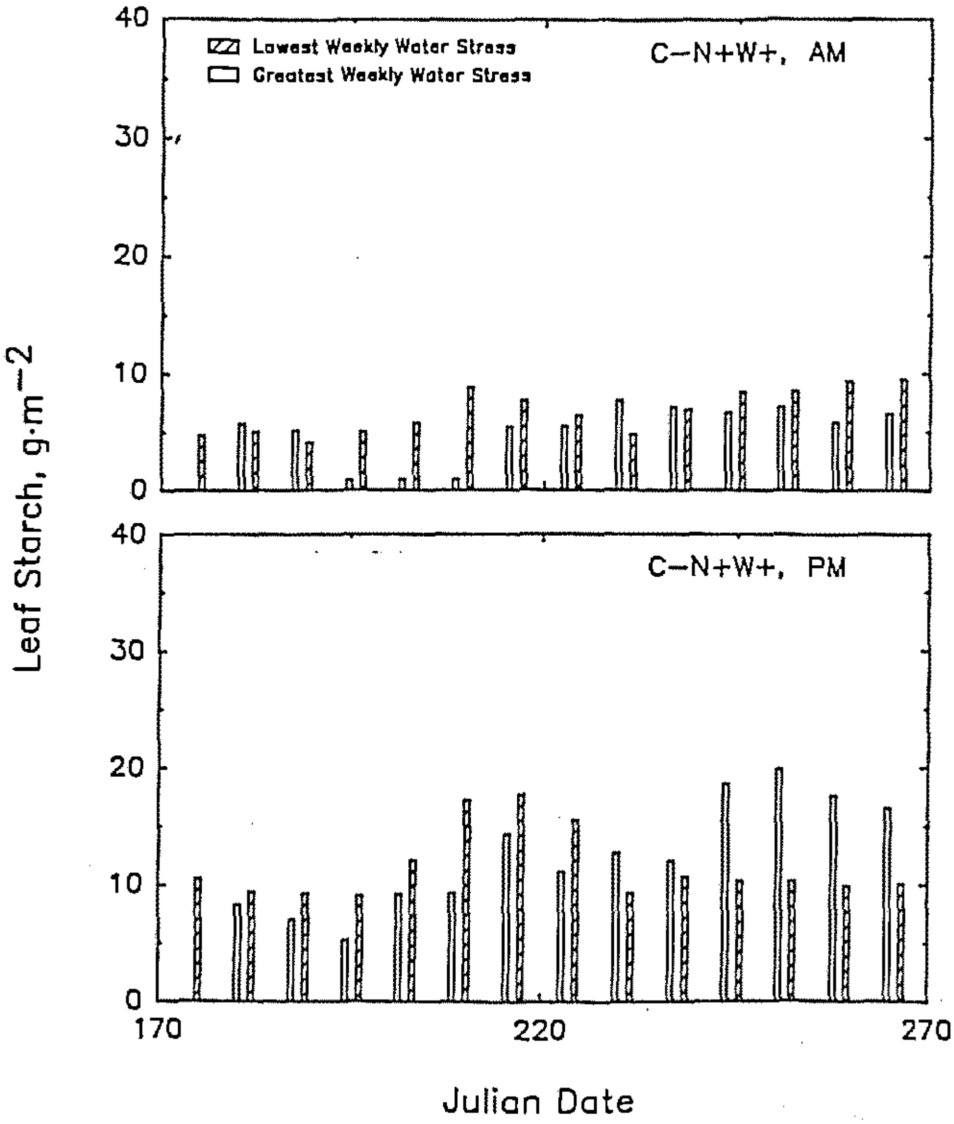

Figure 35. Leaf starch content of chamber-grown cotton plants grown with ambient CO_2 (C-), added nitrogen fertilizer (N+), and were well-watered (W+). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

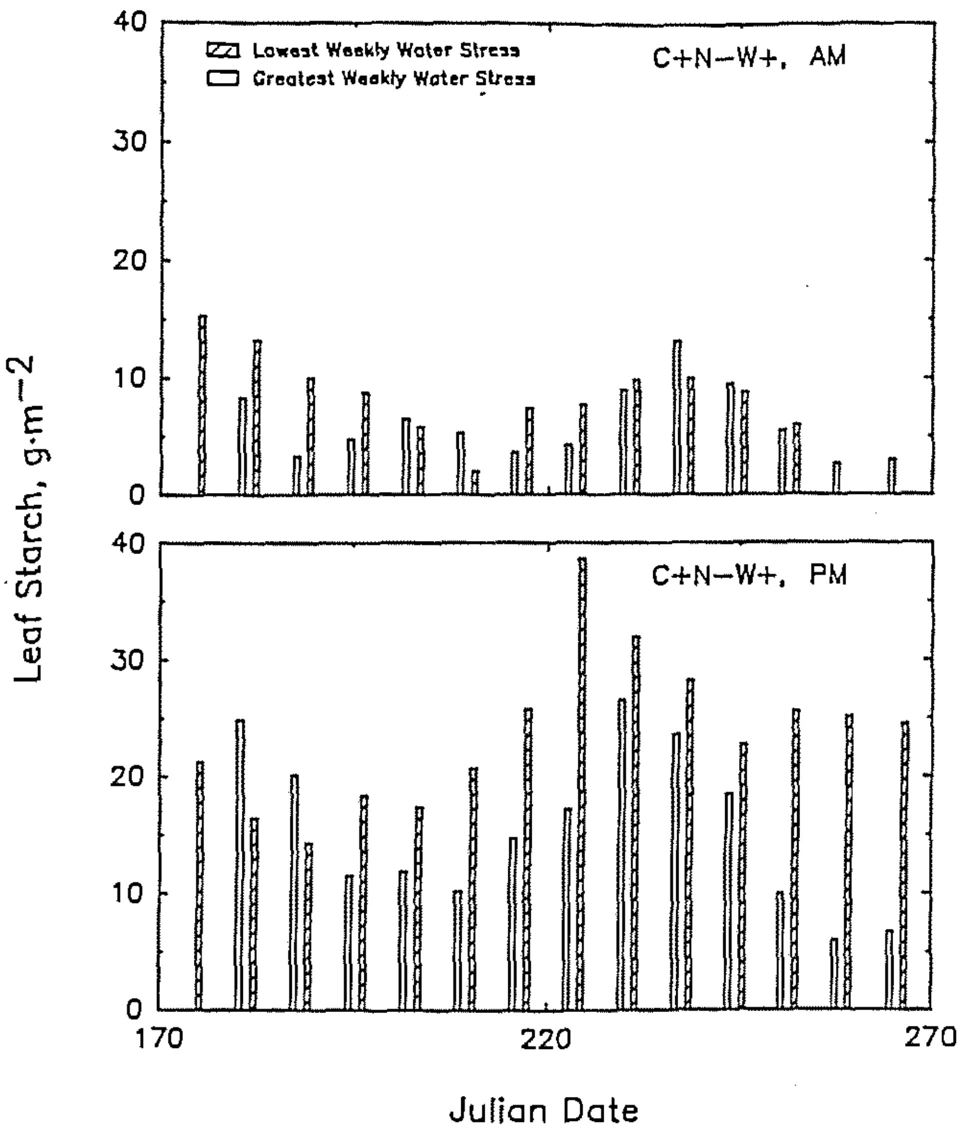

Figure 36. Leaf starch content of chamber-grown cotton plants grown with 650 $\mu\ell/\ell$ CO_2 (C+), no added nitrogen (N-), and were well-watered (W+). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

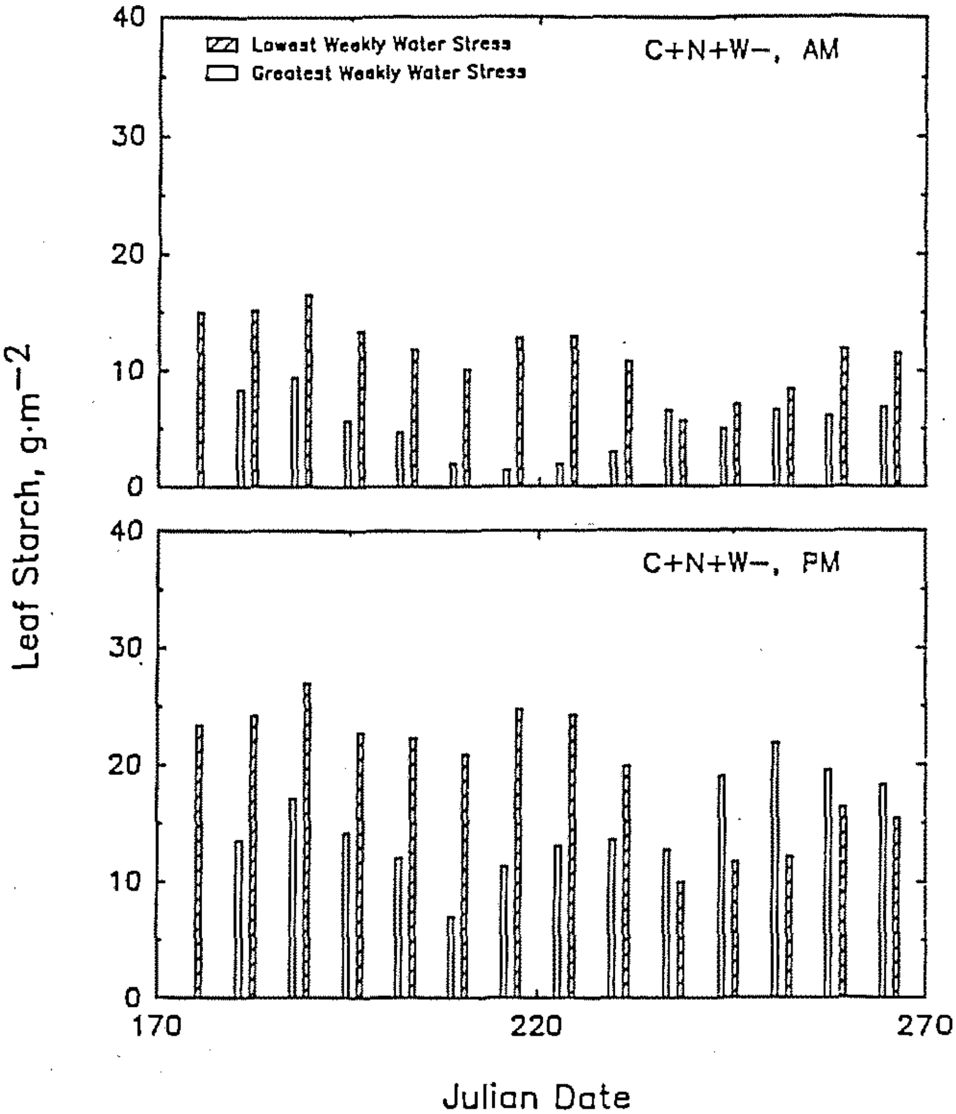

Figure 37. Leaf starch content of chamber-grown cotton plants grown with 650 $\mu\ell/\ell$ CO_2 (C+), added nitrogen (N+), and water-stress (W-). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

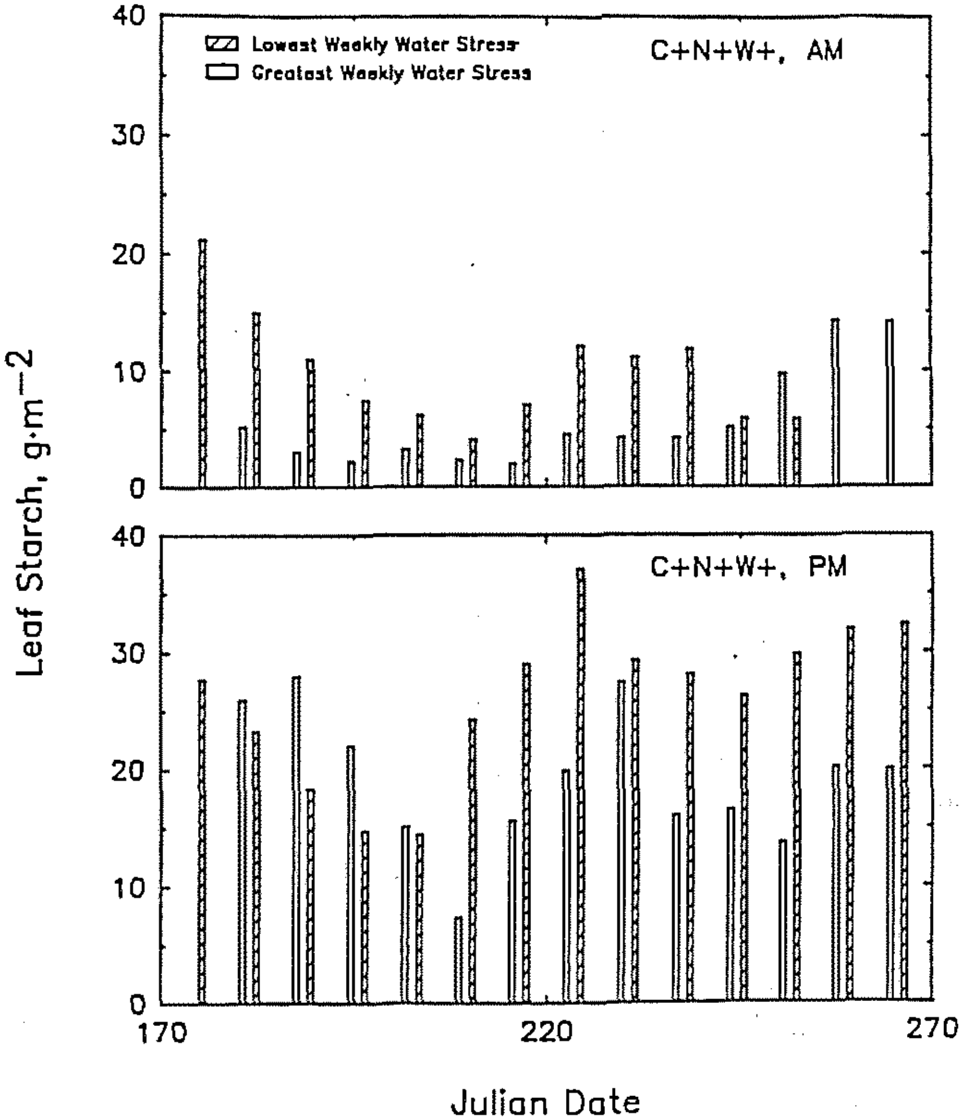

Figure 38. Leaf starch content of chamber-grown cotton plants grown with 650 $\mu\ell/\ell$ CO_2 (C+), added nitrogen (N+), and were well-watered (W+). The same leaves on a plant were sampled at dawn (AM) and dusk (PM) to determine the effect of daily photosynthesis upon this parameter. Plants were sampled two days following watering (lowest weekly water stress) and six days after watering (greatest weekly water stress). Sampling for this test was done using the same plant, sampling the fifth leaf from the apex for the first sample and the leaf just below that for the second sampling. Each bar represents the mean of two replicates.

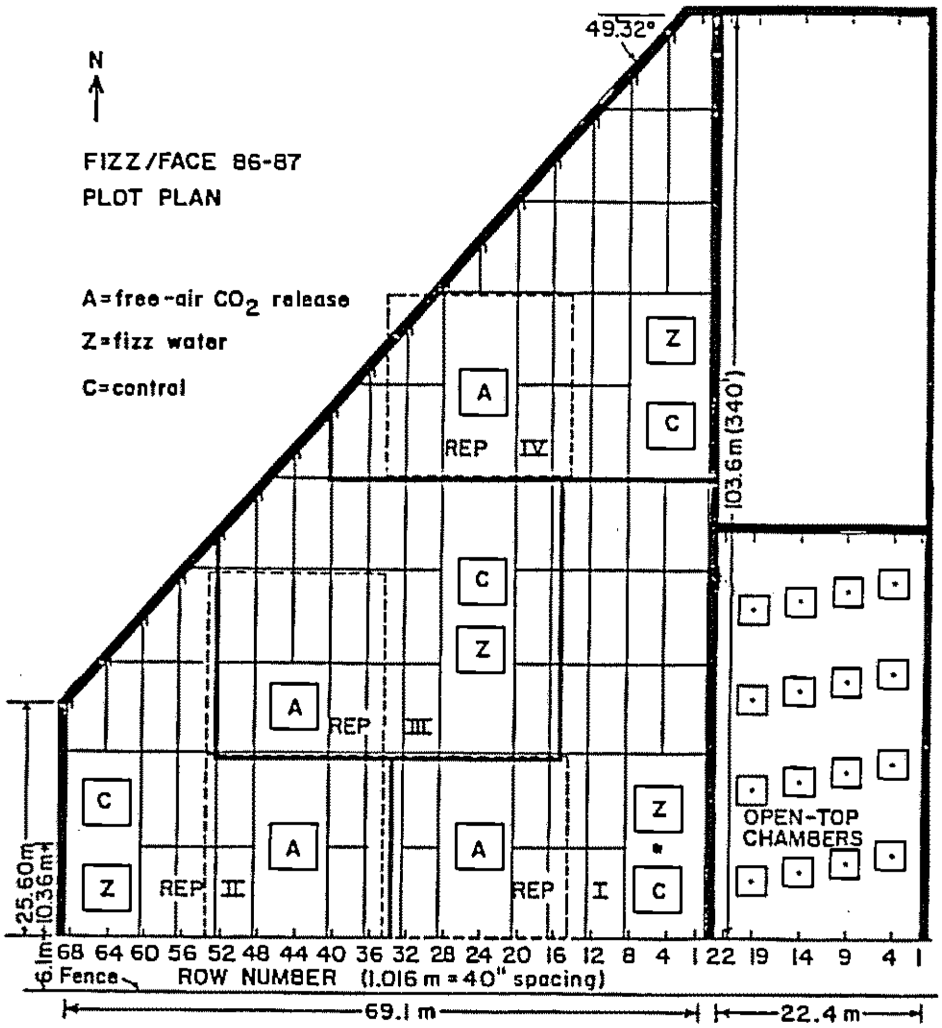

Figure 39. Plot plans for the 1986 and 1987 FIZZ/FACE experiments which were nearly identical. The medium heavy lines demarcate the separate 4 replicates which were irrigated individually, except that the FIZZ plots were irrigated together both years and the control plots were irrigated together only in 1987. The small fine lines demarcate small rectangular plots for an independent plant breeding experiment. The dashed lines demarcate the 20 m borders of the CO_2-enriched area for each of the FACE (A) plots. Rows 36 and 37 were not planted in 1987. The relative location of the open-top chambers for the CO_2/WATER/NITROGEN experiment is also shown. The asterisk (*) indicates the site of the weather mast.

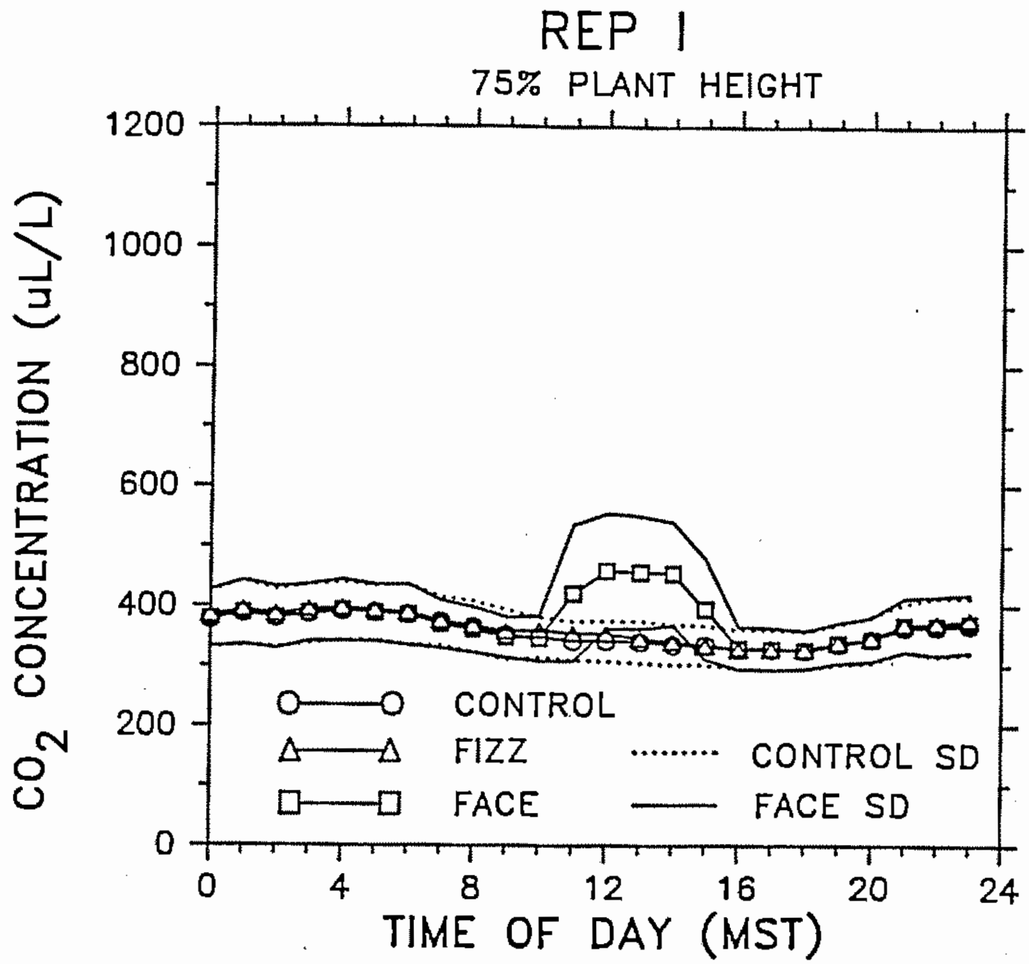

Figure 40. Diurnal course of mean CO_2 concentration averaged from 20 June through 19 September 1987 at the 75% plant height in Rep I of the control, FIZZ, and FACE plots. Also shown are the standard deviations of the individual observations for the control and FACE plots.

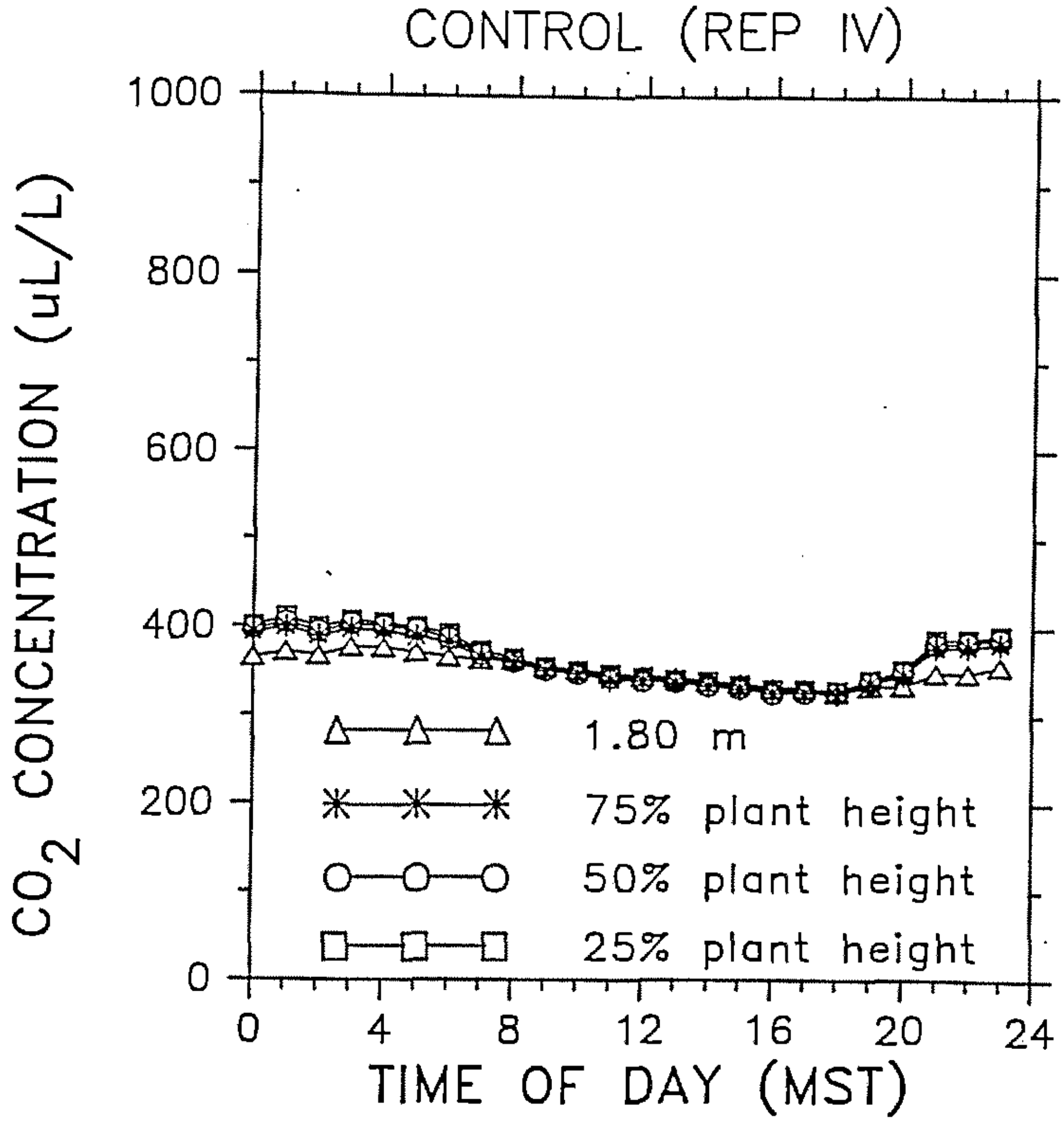

Figure 41. Diurnal course of mean CO_2 concentration averaged from 20 June through 19 September at various heights in the Rep IV control plot.

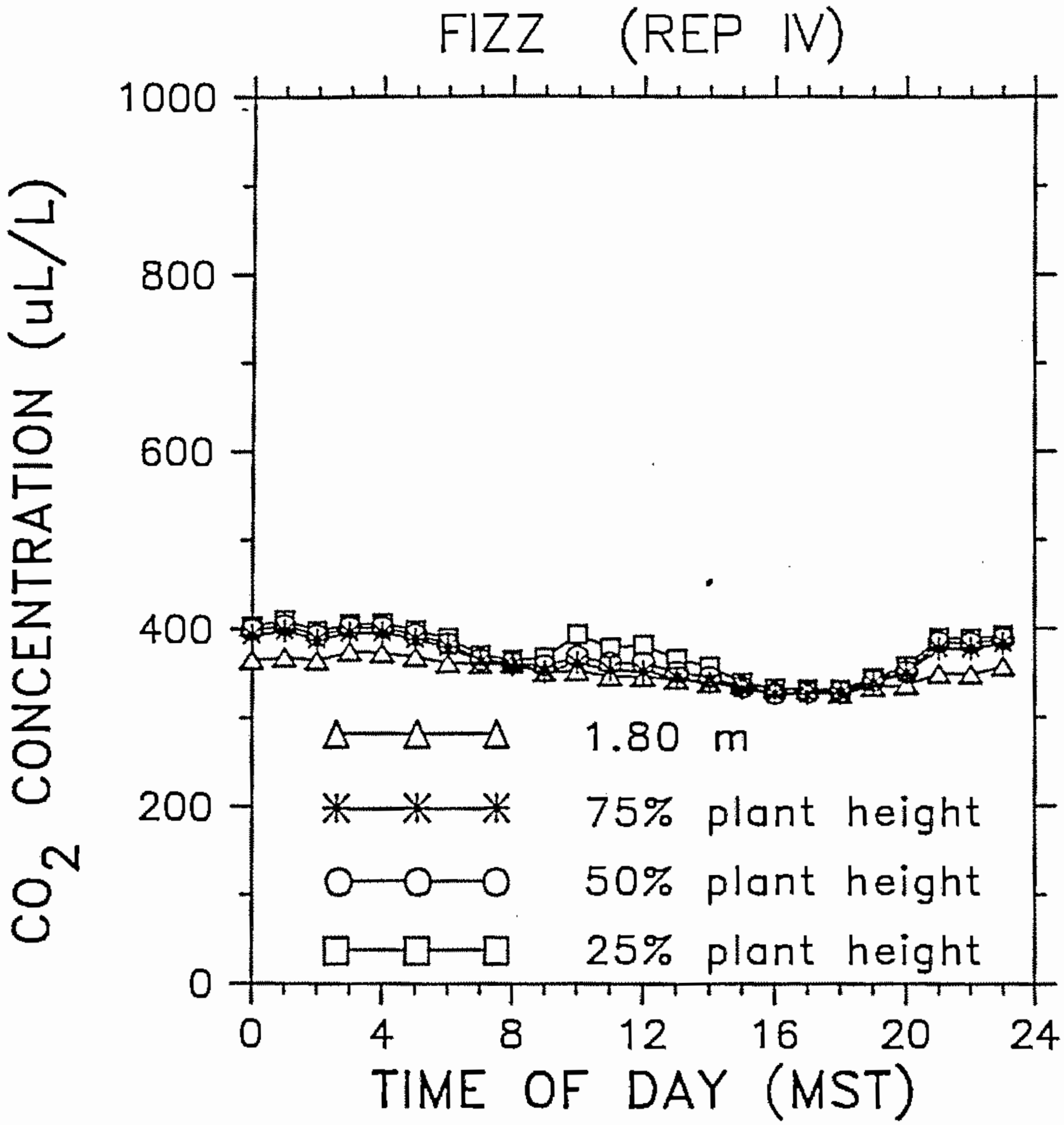

Figure 42. Diurnal course of mean CO_2 concentration averaged from 20 June through 19 September at various heights in the Rep IV FIZZ plot.

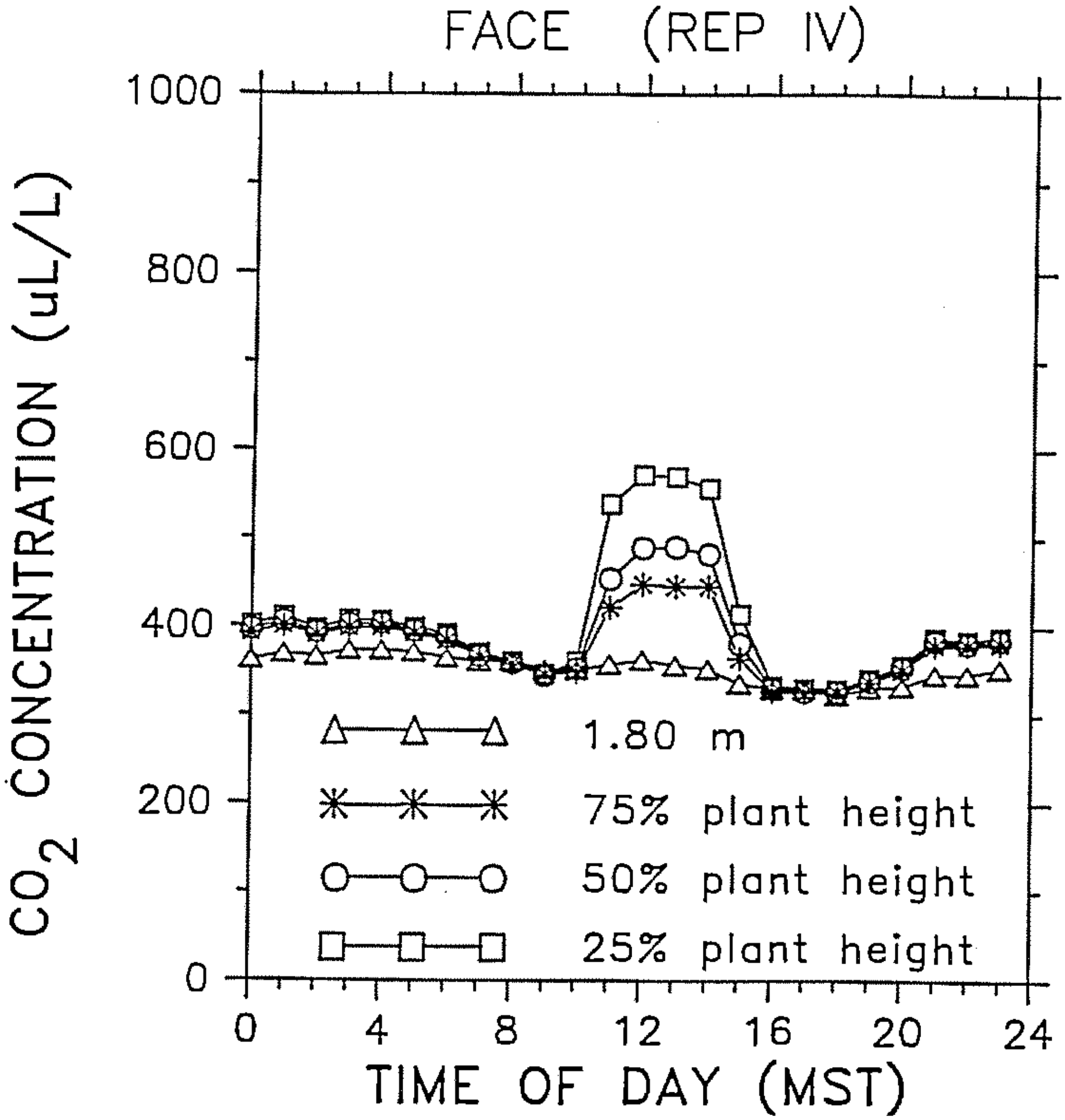

Figure 43. Diurnal course of mean CO_2 concentration averaged from 20 June through 19 September at various heights in the Rep IV FACE plot.

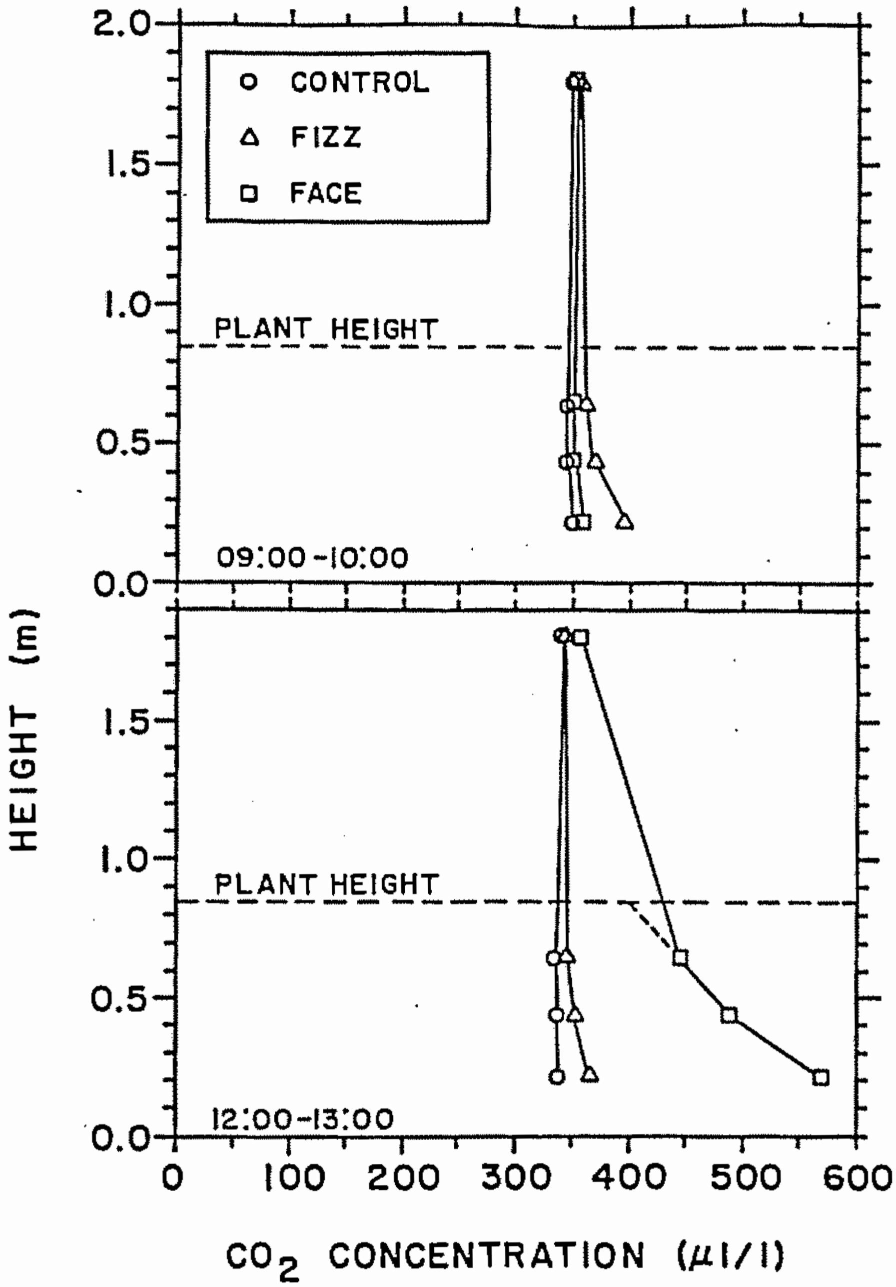

Figure 44. Vertical profiles of mean CO_2 concentration sampled during the hours ending about 10:00 (upper graph) and about 13:00 (lower graph)

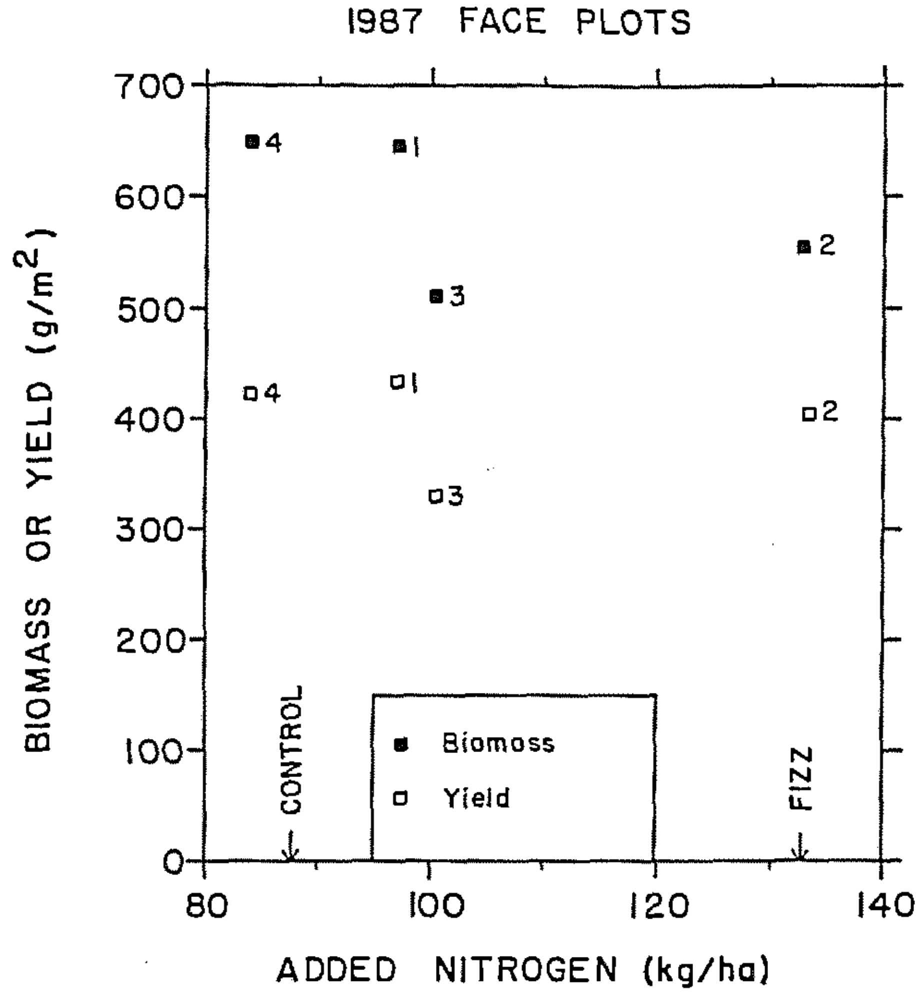

Figure 45. Final biomass and seed cotton yields from the 1987 FACE experiment plots versus the amount of applied nitrogen fertilizer. The numbers beside the data points identify the particular rep. The arrows indicate the amounts applied to the control and FIZZ plots.

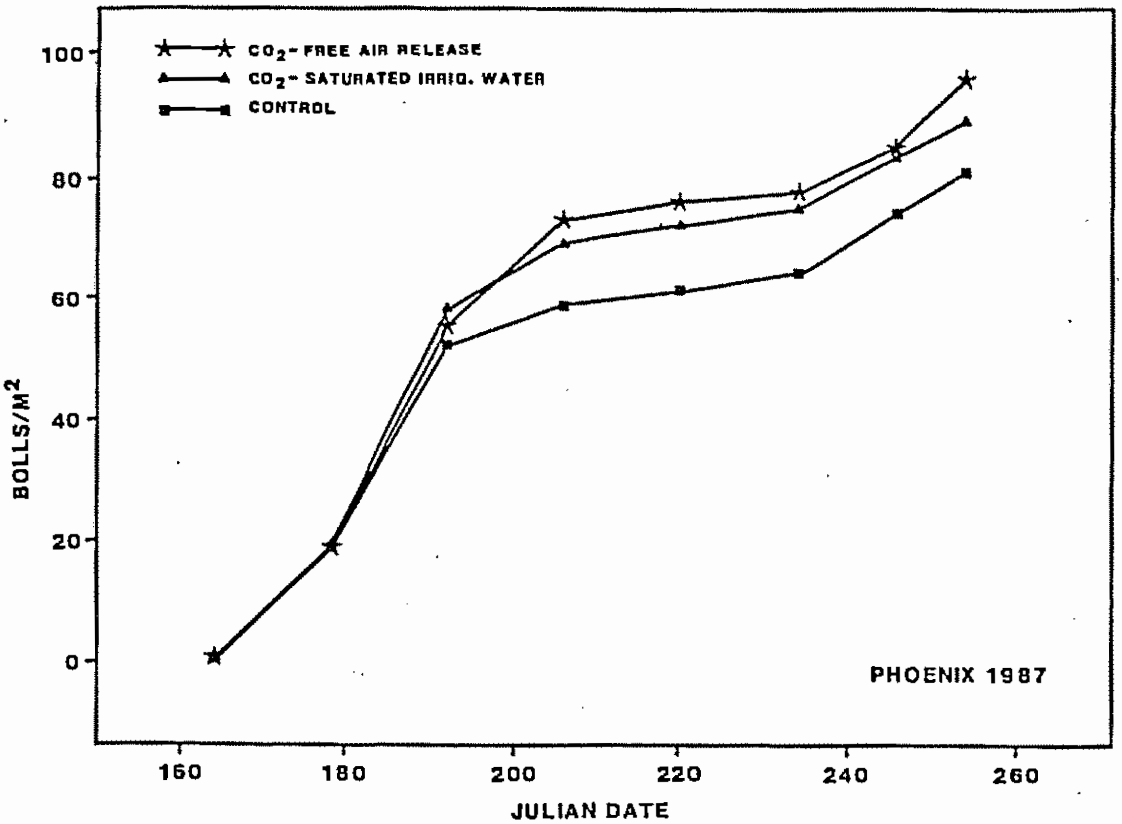

Figure 46. Accumulated number of bolls through the season in the 1987 FIZZ/FACE experiment. The data are weekly averages of four replicates.

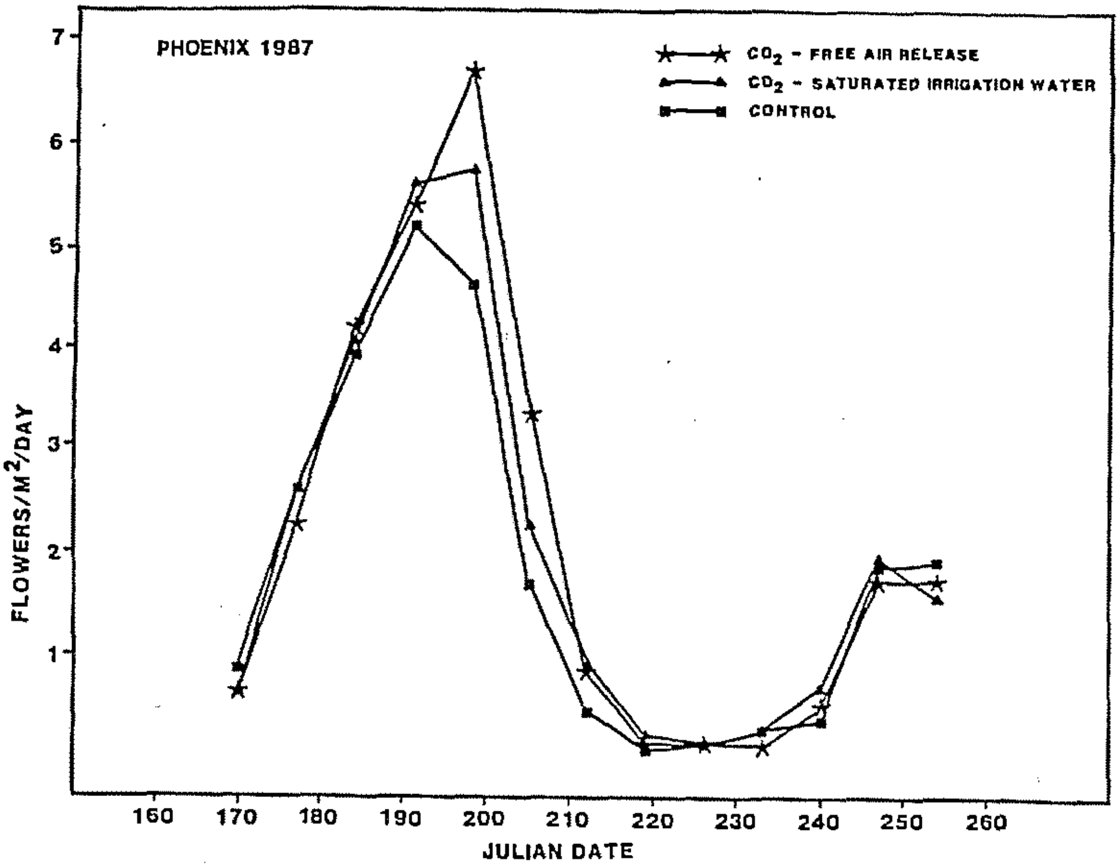

Figure 47. Rate of flower production in the 1987 FIZZ/FACE experiment. The data are weekly averages of four replications.

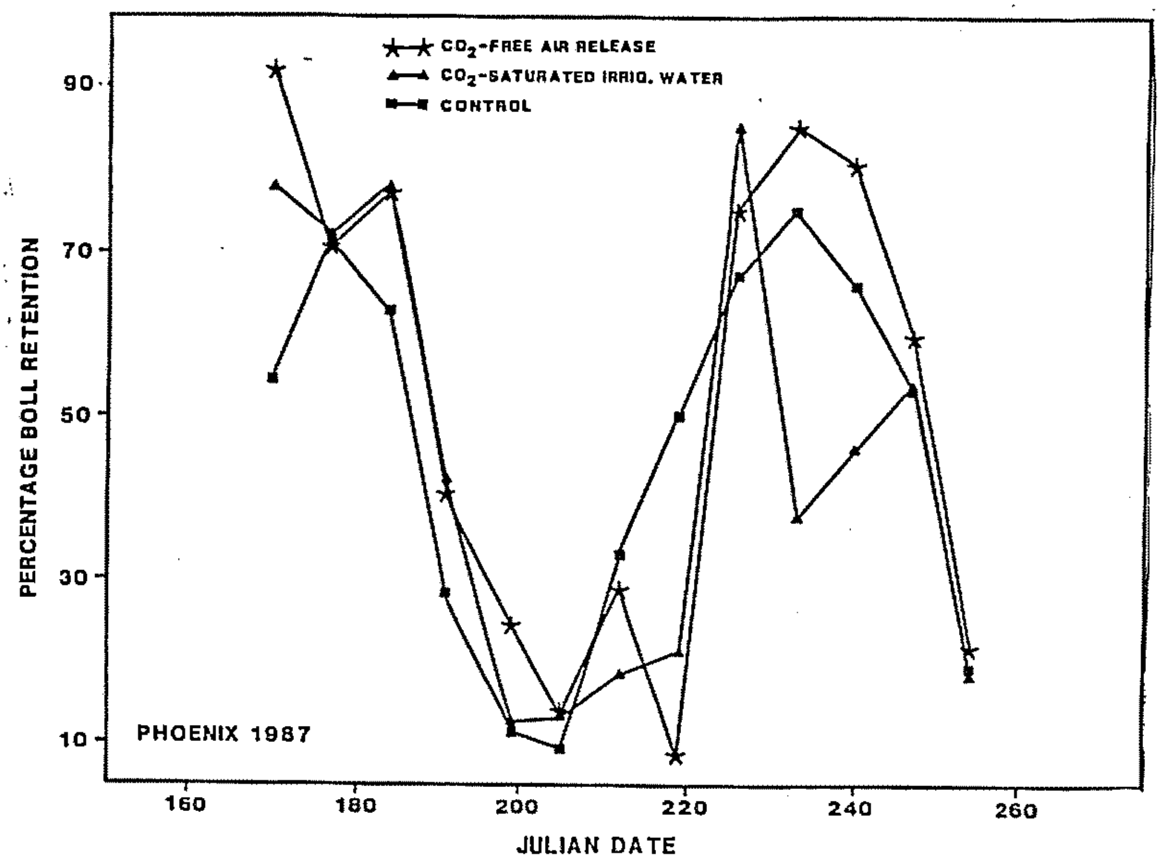

Figure 48. Boll retention in the 1987 FIZZ/FACE experiment. The data are the percentages of the weekly averages (and over 4 replications) of blossoms produced which resulted in harvestable bolls.

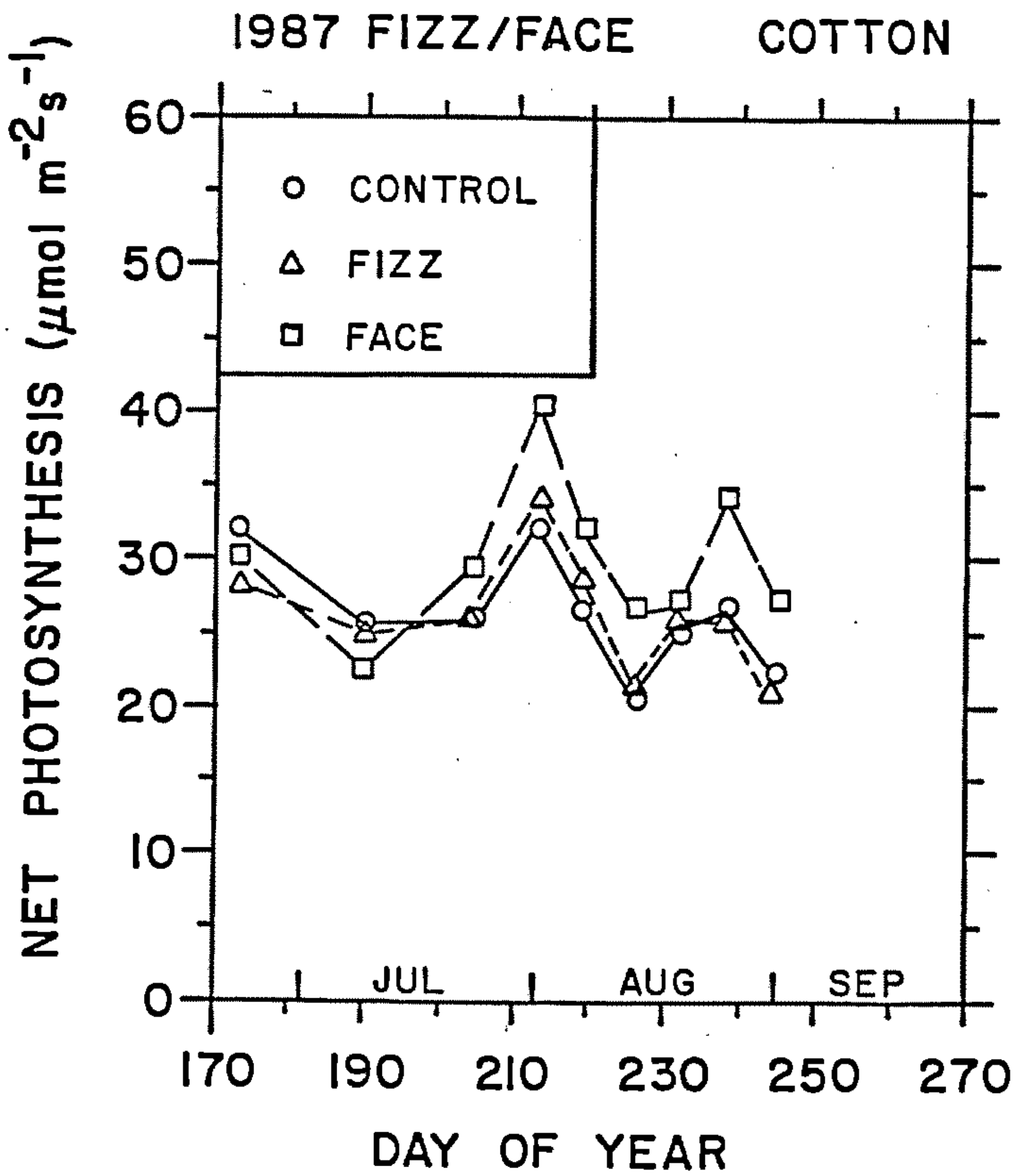

Figure 49. Net photosynthesis of cotton leaves versus day of year (1987) for the FIZZ/FACE experiment. Each data point is an average over three leaves per plot and 4 reps.

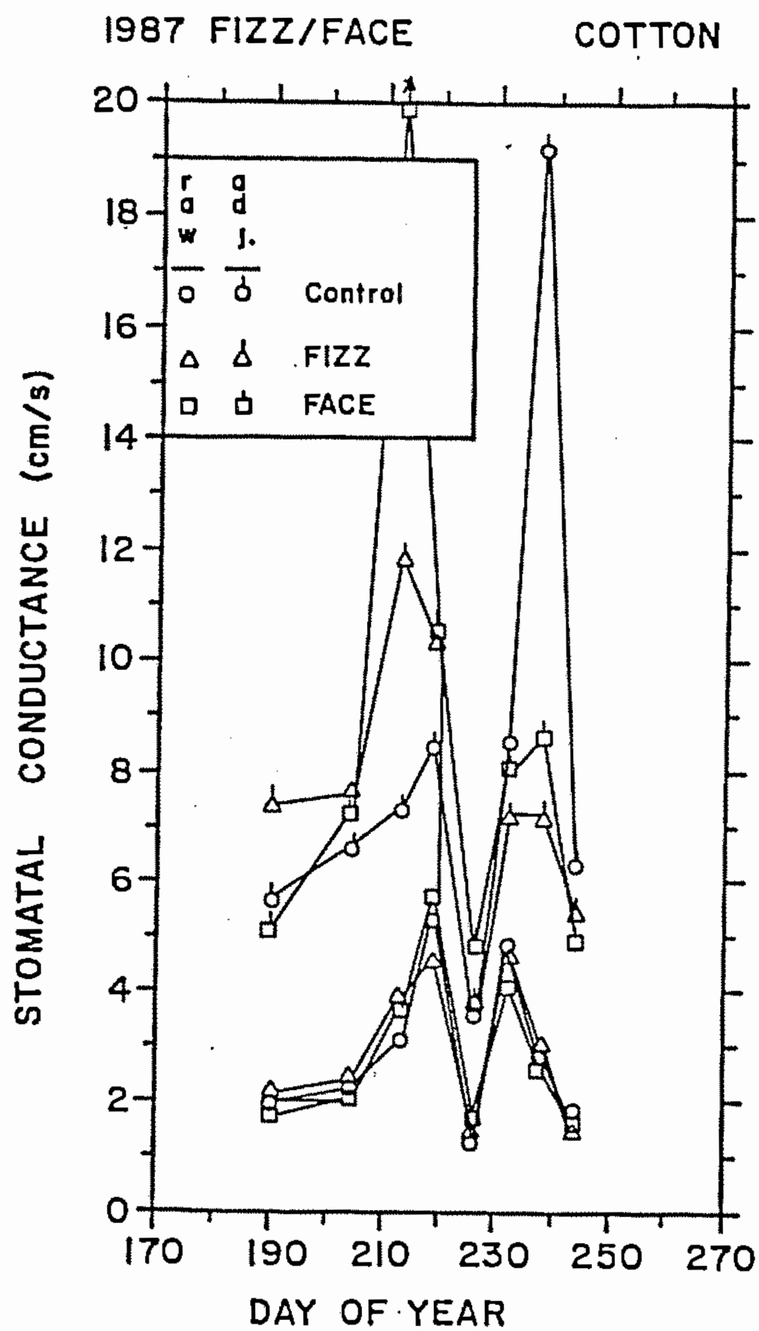

Figure 50. Stomatal conductance of cotton leaves versus day of year (1987) for the FIZZ/FACE experiment. Each point is an average over 3 leaves per plot and 4 reps. Both "raw" conductance values and also "adjusted" values are plotted, where the adjustment was accomplished following the recommended procedure of Idso et al. (1987).

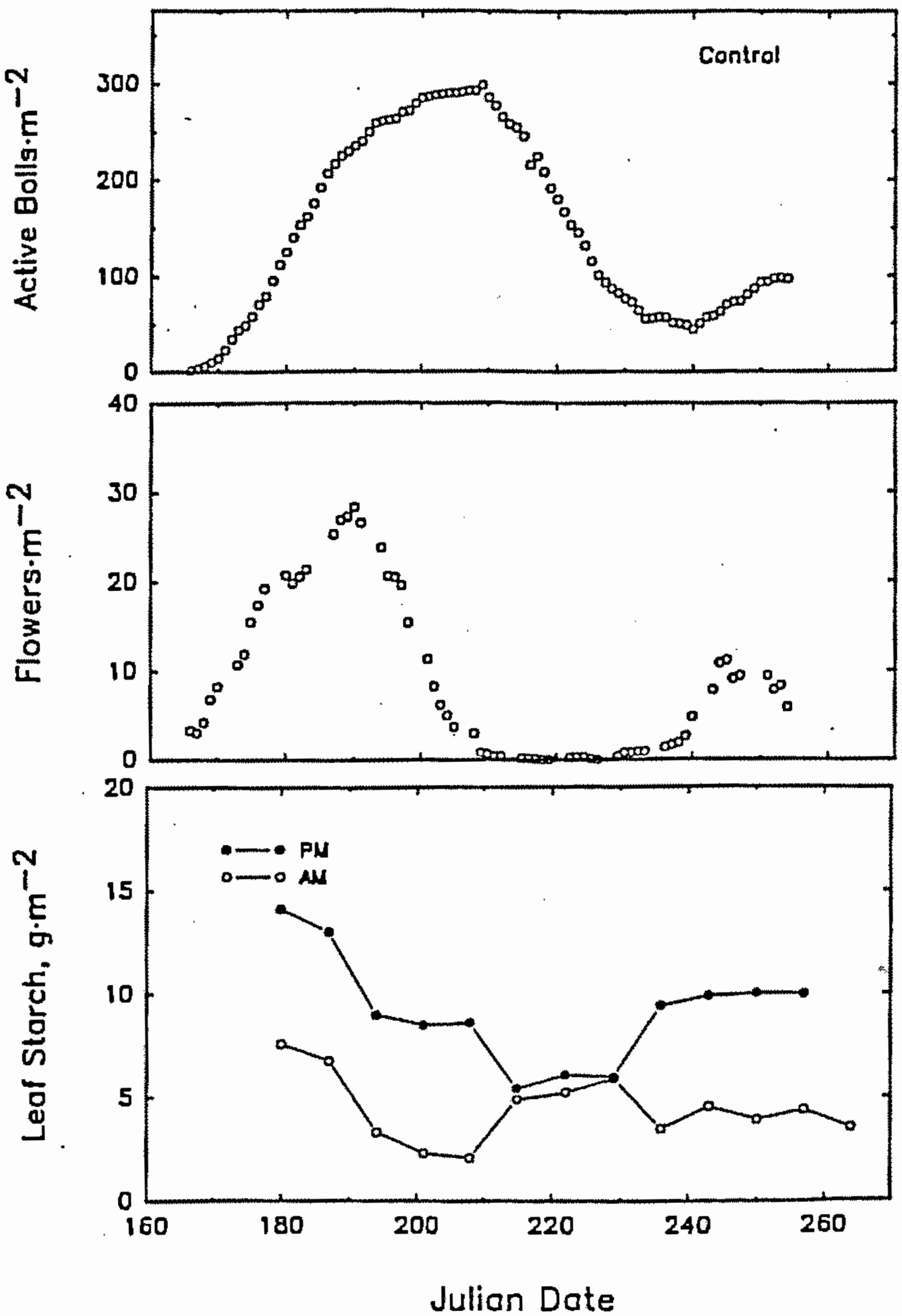

Figure 51. Starch in cotton leaves in the control plots of the 1987 FIZZ/FACE experiment sampled once each week at dawn and dusk versus day of year. Leaves five nodes from the apex were sampled in each plot. Each point represents the mean of four replicates. Also shown are the number of active bolls (i.e., no more than 40 days old) and the number of flowers.

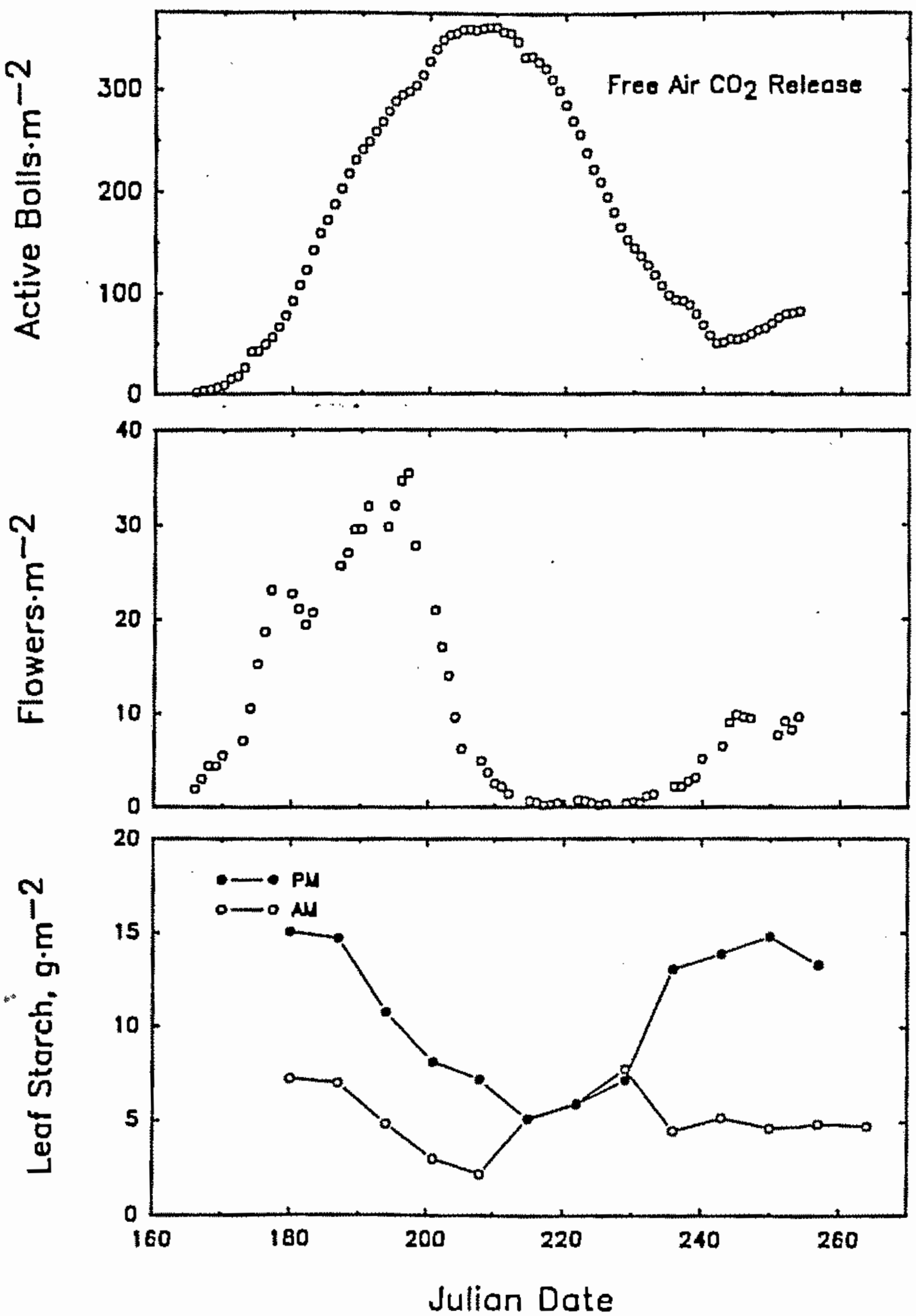

Figure 52. Starch in cotton leaves in the free-air CO_2 enrichment (FACE) plots of the 1987 FIZZ/FACE experiment sampled once each week at dawn and dusk versus day of year. Leaves five nodes from the apex were sampled in each plot. Each point represents the mean of four replicates. Also shown are the number of active bolls (i.e., no more than 40 days old) and the number of flowers.

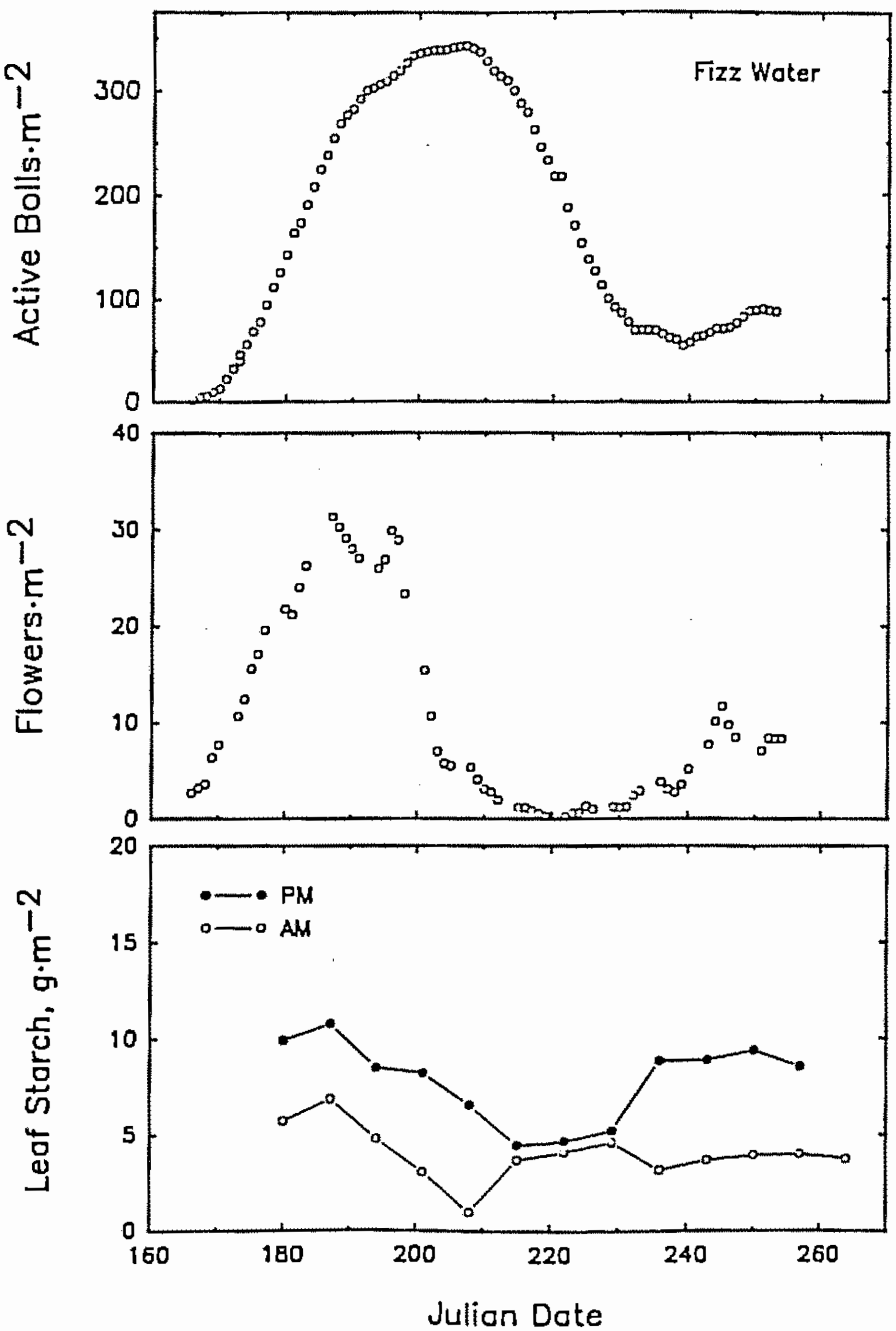

Figure 53. Starch in cotton leaves in the carbonated-water-irrigated (FIZZ) plots of the 1987 FIZZ/FACE experiment sampled once each week at dawn and dusk versus day of year. Leaves five nodes from the apex were sampled in each plot. Each point represents the mean of four replicates. Also shown are the number of active bolls (i.e., no more than 40 days old) and the number of flowers.

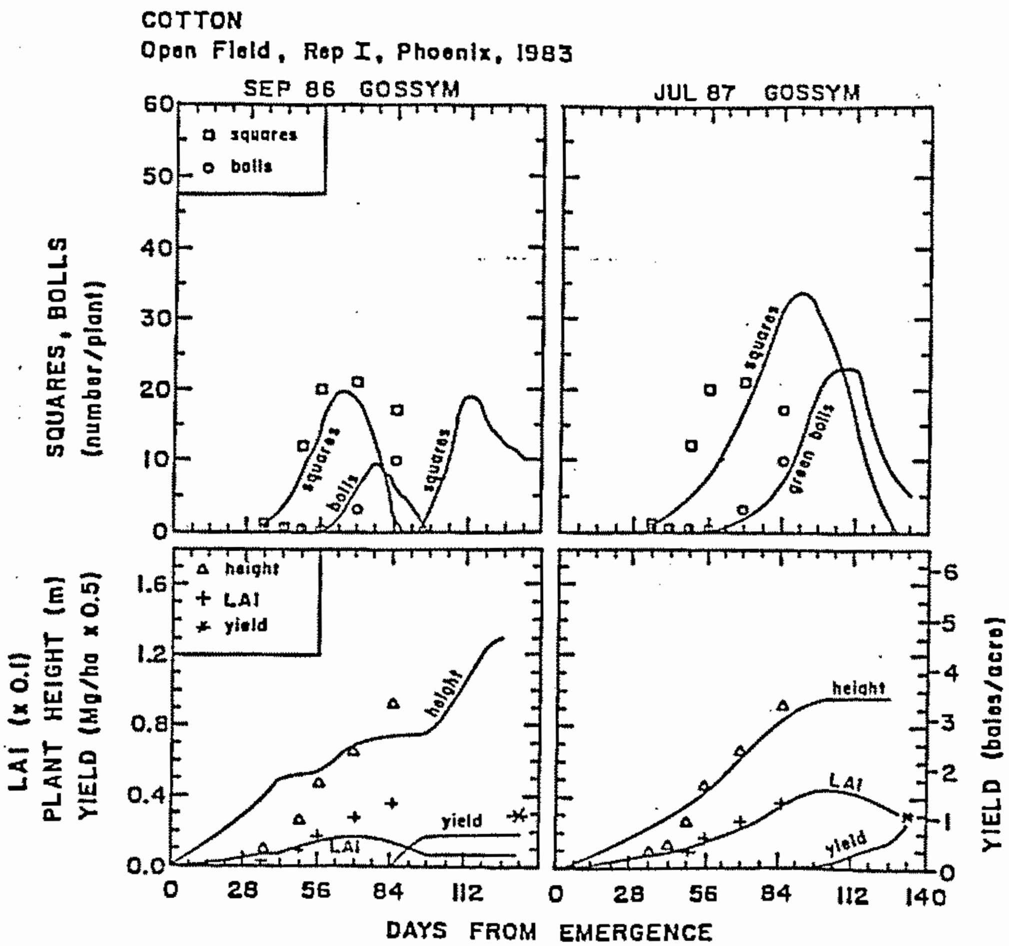

Figure 54. Comparison between GOSSYM predictions and observations [open field, Rep I, from Kimball et al. (1983) experiment] of plant height, leaf area index (LAI), yield, number of squares, and number of bolls using September 1986 (left side) and July 1987 (right side) versions of GOSSYM.

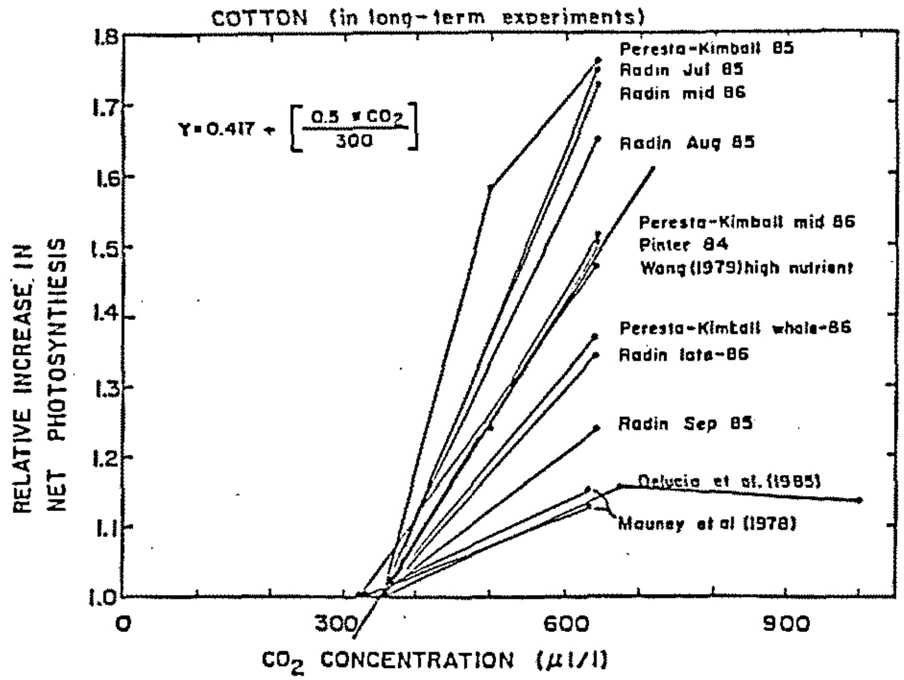

Figure 55. Relative increase in net photosynthesis as a function of the external CO_2 concentration as observed by Mauney et al. (1978); Wong (1979); Pinter, Radin, and Peresta-Kimball (Kimball et al., 1984, 1985, 1986); and DeLucia et al. (1985). Also shown is a linear equation fitted by eye.

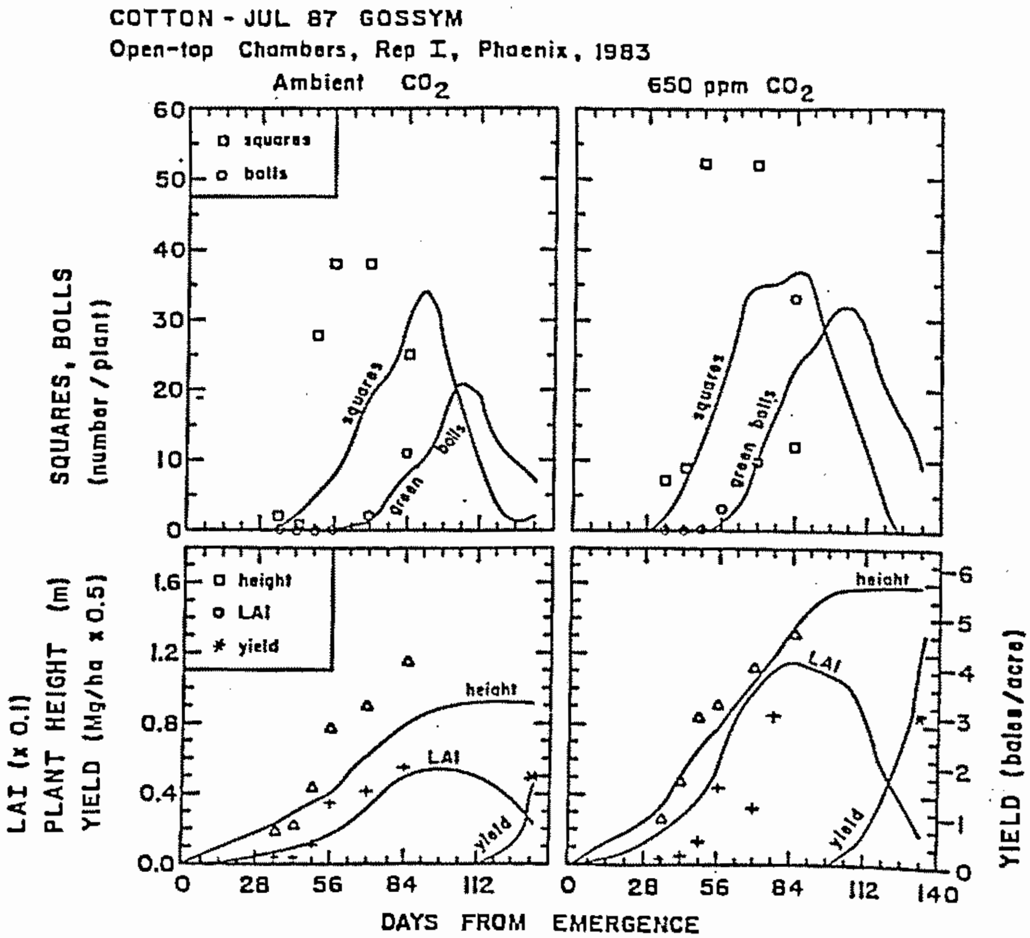

Figure 56. Comparisons between July 1987 GOSSYM predictions and observations [Rep I, from Kimball et al. (1983) experiment] of plant height, leaf area index (LAI), yield, number of squares, and number of bolls for ambient CO_2 (left side) and 650 ppm CO_2 (right side) concentrations in open-top chambers.

TITLE: SPATIAL VARIABILITY OF DEEP PERCOLATION RATES

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-20790-005

INTRODUCTION

Characterization of solute movement through the root zone to the groundwater is necessary to predict the long term effects of irrigation on groundwater quality. The ability to predict the rate of solute movement and the resulting quality of the deep percolation water is critical for evaluation of irrigation management practices on groundwater quality. In order to predict the movement of solutes and pesticides through the soil to the groundwater, we must also know how the solute velocities vary over space and time.

PROCEDURE

Spatial and temporal variability studies of water and solute transport were conducted at the Maricopa Agricultural Center. The experiment was described in detail in the 1985 Annual Report, "Distribution of a mobile herbicide below a flood irrigated field." Five 7.5 cm irrigations were applied to the field at 2 week intervals. A different tracer was applied to 14 plots before each irrigation. Six days after the last irrigation each plot was sampled at seven random locations at 30 cm intervals to a depth of 270 cm. For analysis, a 2:1 soil-water extract was obtained for each sample and analyzed using a HPLC method.

RESULTS AND DISCUSSION

Velocity and dispersion coefficients were determined for each hole by fitting the data to the one dimensional convection-dispersion equation using the non-linear least squares inversion method. Examples of the fitted curves are shown in Fig. 1 as the smoothed curves. Fractile diagrams of velocity indicated a normal distribution as shown in Fig. 2. However, the dispersion coefficients appeared to be log-normally distributed as shown in Fig. 3.

The variation of solute velocity over time was analyzed from each location sampled. From the depth-concentration relationships, as shown in Fig. 1, the depth of the maximum concentration, D_m, of each tracer was determined. Because each tracer was applied at a different time, the breakthrough curves, shown in Fig. 1, are representative of solute movement over time. A linear relationship of D_m and time indicates constant velocity over time. Linear regression analysis was run on each D_m-time curve. The average r^2 value for all 98 holes was 0.91 +/- 0.1 which indicates that little variation in velocity occurred over time. When smoothed data was used, the r^2 value increased to 0.95.

The spatial structure of the field was characterized using semi-variagrams for velocity. The semi-variagrams for each tracer are shown in Fig. 4. The minimum number of pairs used for any one lag was 30. The minimum distance between sample points was 1.5 m. The sill fluctuated around the variance in all variagrams. The amplitude of the fluctuation and the variance increased at smaller times. The samples were taken in 30 cm increments. At the smaller times, the tracer had moved a shorter distance. The 30 cm increment then represented a larger percentage of the total depth. Errors in defining the actual depth of tracer peak would be greater then at the shallower depths or smaller times. The range varied from 3 m at day 69 to about 7 m at day 6. The greatest change in the range was noted between days 6 and 27. However, because of the greater variance and fluctuation in the variagram, a larger error in range estimation would be expected. The magnitude of the range is similar to that determined from previous infiltration studies on the same field. The range associated with spatial variation of evaporation was also between 3 and 7 m. However, one would not expect the spatial structure of evaporation to necessarily be similar to that of infiltration or solute velocity.

SUMMARY AND CONCLUSIONS

Spatial and temporal variability of solute velocity was studied under intermittent flood irrigation. The velocity was normally distributed while the dispersion coefficients were log-normally distributed. The velocity at any one sample point in the field varied little with time over the 70 day duration of the experiment. The spatial variability of solute velocity was characterized by semi-variagrams. The range varied from about 3 m at day 69 to 7 m at day 6.

PERSONNEL

R. C. Rice, D. B. Jaynes, G. C. Auer, J. B. Miller, H. Bouwer, and H. Y. Cho

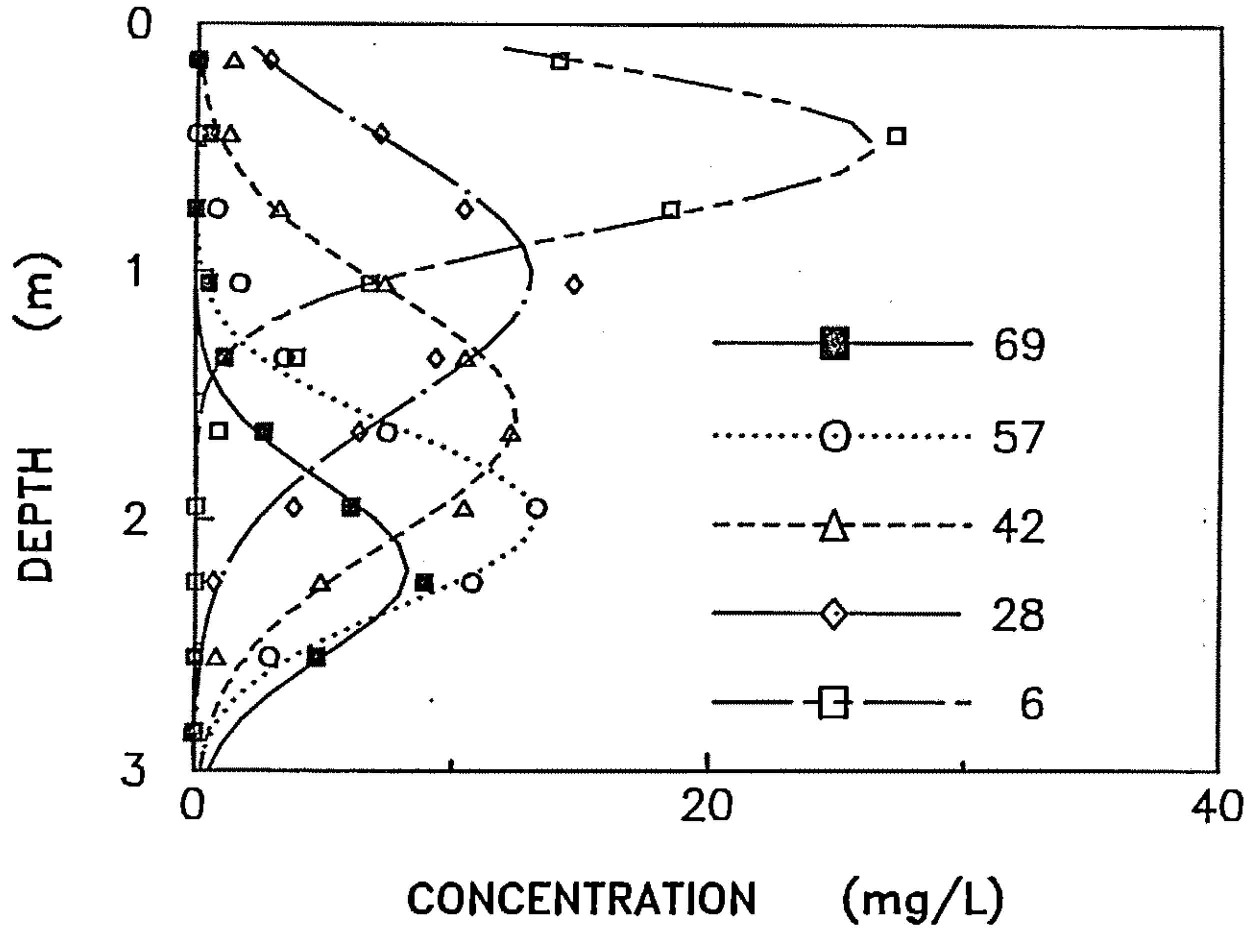

Figure 1. Depth concentration curves for five different times (on the curves). Actual data is represented by points. Curves are fitted data.

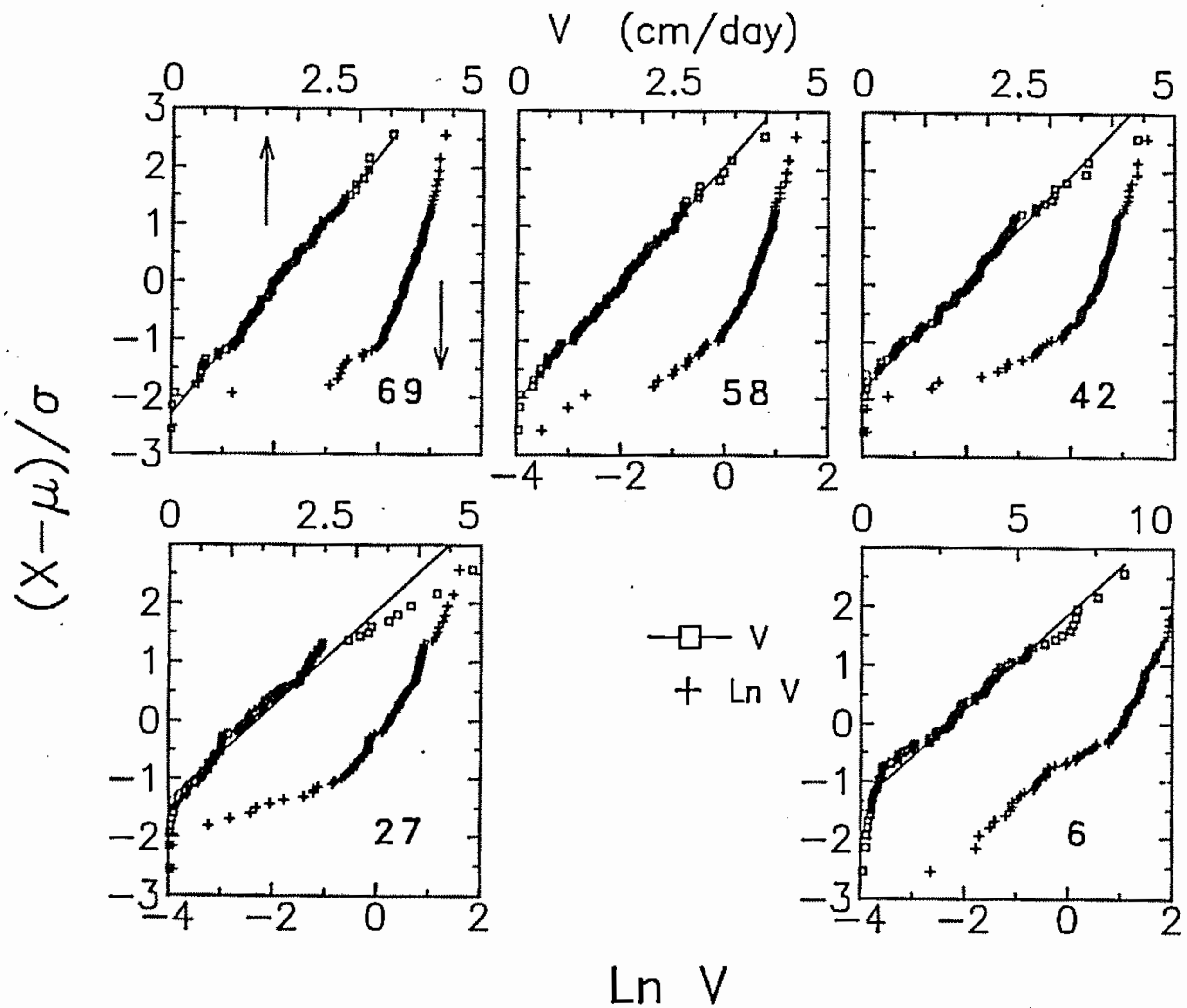

Figure 2. Fractile diagram of velocity for linear and log-transformed data.

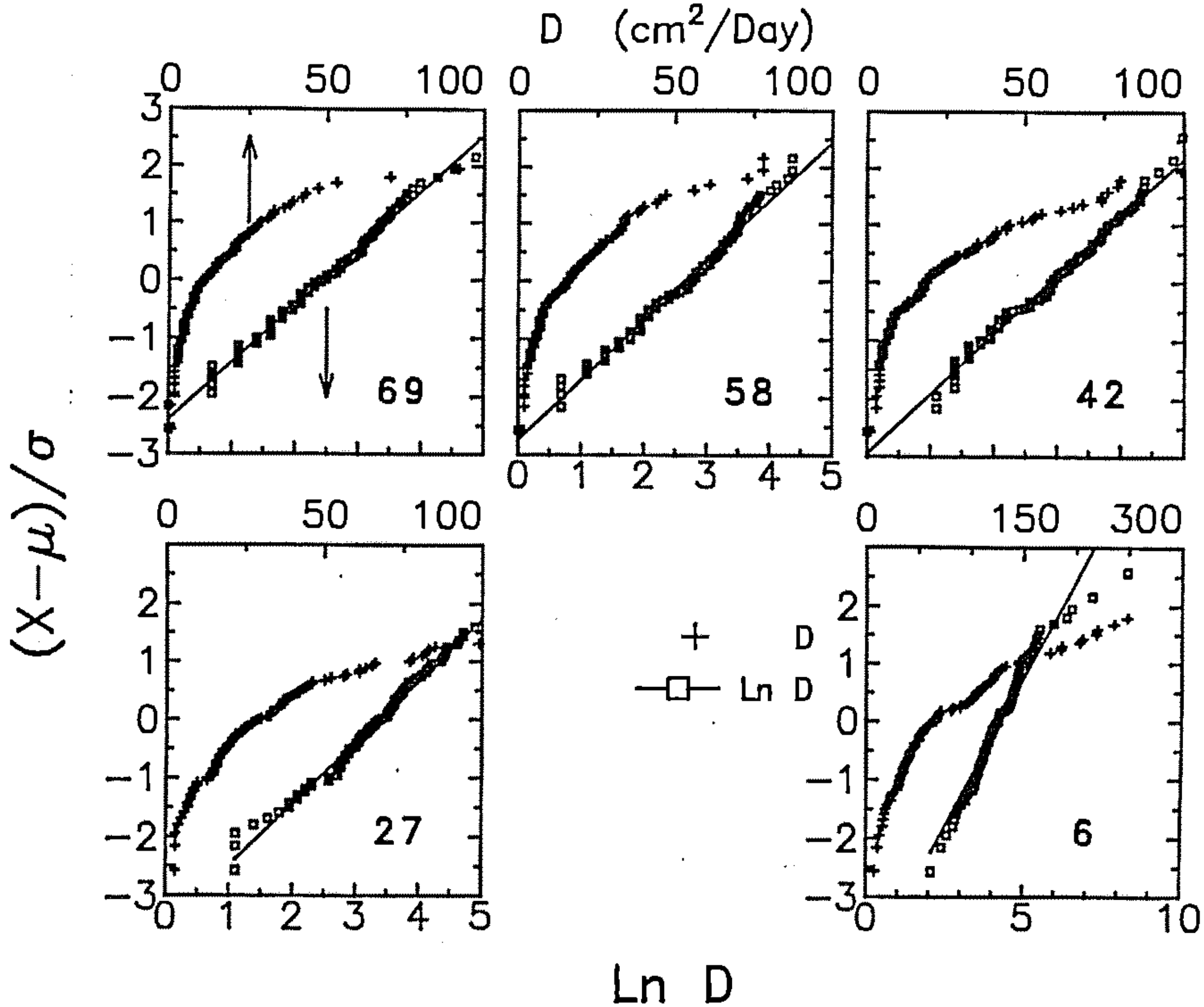

Figure 3. Fractile diagram of dispersion coefficient for linear and log-transformed data .

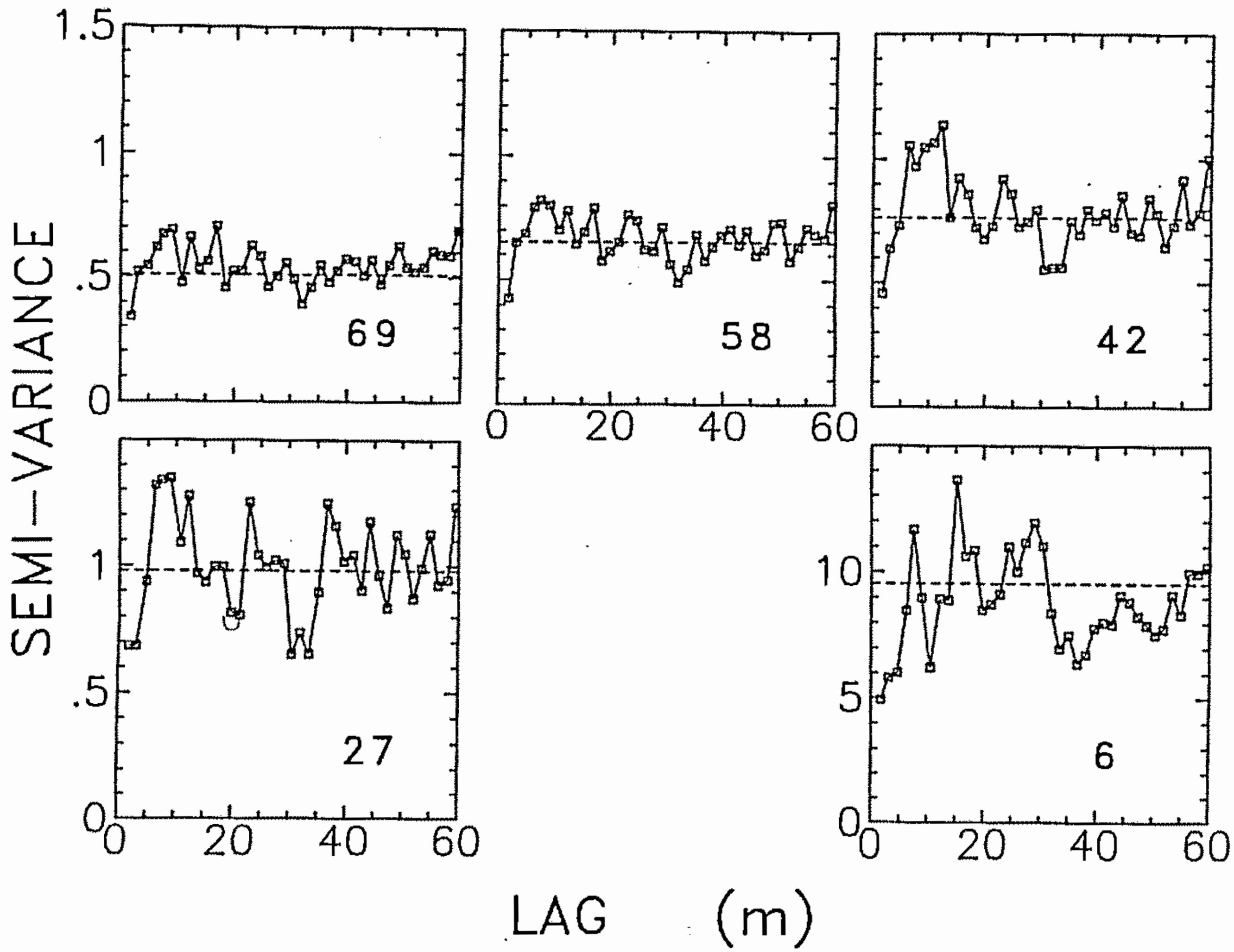

Figure 4. Semivariagrams for velocity at different times. Dashed line represents the variance.

TITLE: Transport of a Conservative Tracer in the Field Under Continuous Flood Irrigation

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-20790-005

A 5-cm deep pulse of bromide-tagged water was applied to four small field subplots and then leached under continuously flooded conditions for seven days. During leaching, solution samples were periodically withdrawn through suction samplers from seven depths within each subplot. Pore water velocities, v_s, and dispersion coefficients, D, were calculated by fitting the one-dimensional solution of the advection-dispersion equation to the concentration versus time curves from each sampler. Both v_s and D were best described by a log-normal distribution rather than a normal distribution (Figs. 1 and 2). D values were very large compared to values reported for laboratory experiments, but similar to other field values measured under similar conditions. Neither v_s nor D showed any significant correlation with depth or time but the dispersivity (ratio of D to v_s) did show a weak positive correlation with depth. The relationship between ln D and ln v_s was linear with a slope near 1.0 (Fig. 3). However, when v_s and D data measured in an earlier study under an intermittently dosed irrigation regime at the same site were included, ln D was no longer a simple linear function of ln v_s. This may be due to differences in the flow regime created by these two irrigations schemes or to difficulties in applying an analytical solution for a steady-state flow problem to a intermittently dosed regime.

The ratio between the calculated pore water velocities and the velocities calculated from the surface flux divided by the average water content was equal to or slightly less than 1.0 for all depths below 0.6 meters (Fig. 4a). At depths less than 0.6 m the ratio was considerably greater than 1.0 indicating that a fraction of the soil water was being bypassed or not participating in the leaching process. This result is in contrast to an earlier study conducted under a dosed irrigation scheme on this site in which the ratio was consistently greater than 1.0 at all depths (Fig. 4b). Preferential flow caused by immobile water or large macropores is apparently not as important under continuously flooded conditions as under intermittent conditions at this site.

PERSONNEL

D. B. Jaynes, R. S. Bowman, R. C. Rice, H. Bouwer, and H. Y. Cho

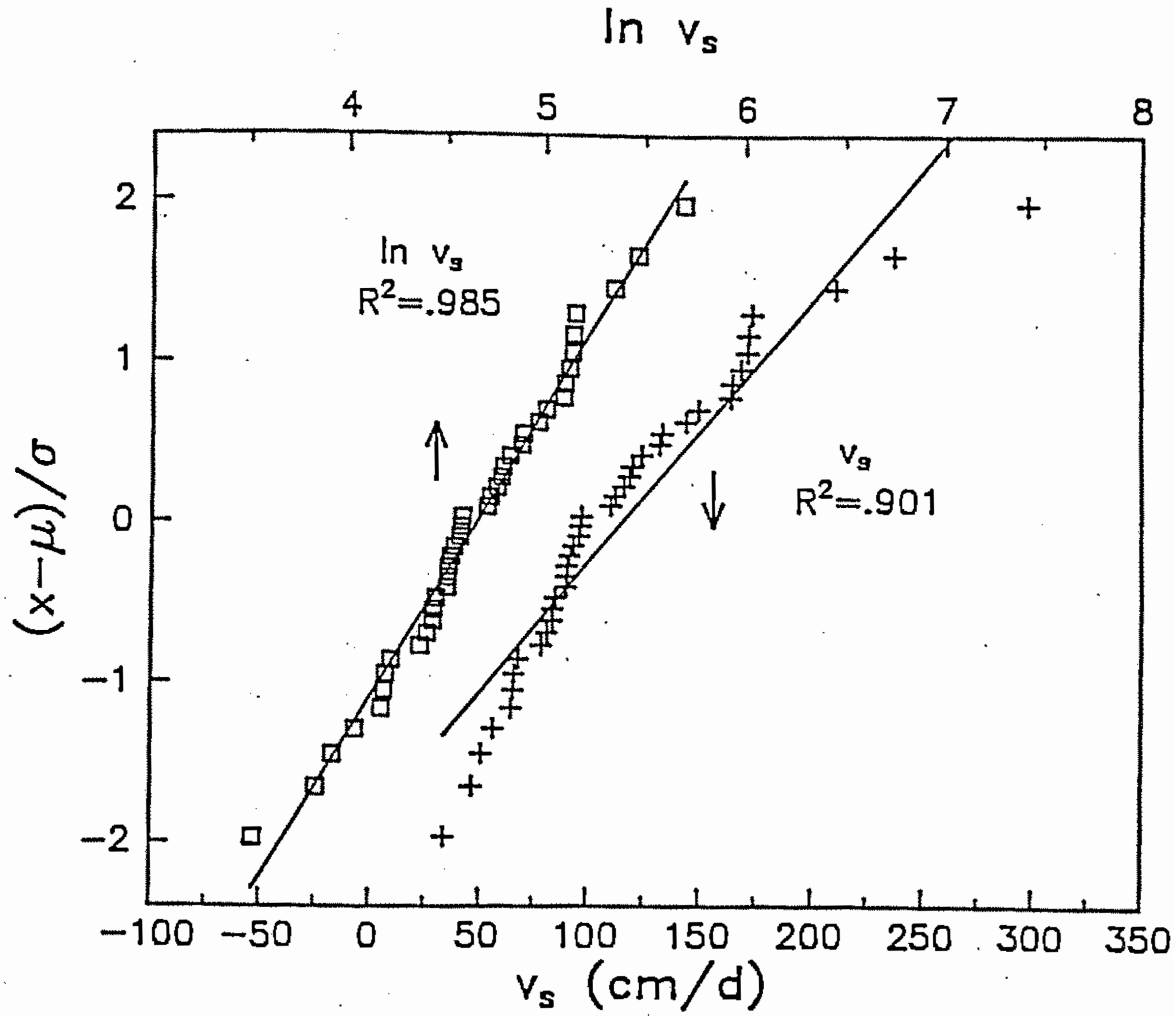

Figure 1. Fractile diagrams for v_s and ln v_s fitted to the continuously flooded irrigation results where μ and σ are the mean and standard deviation of the variable x respectively. R^2 values refer to the goodness of fit to a linear relation.

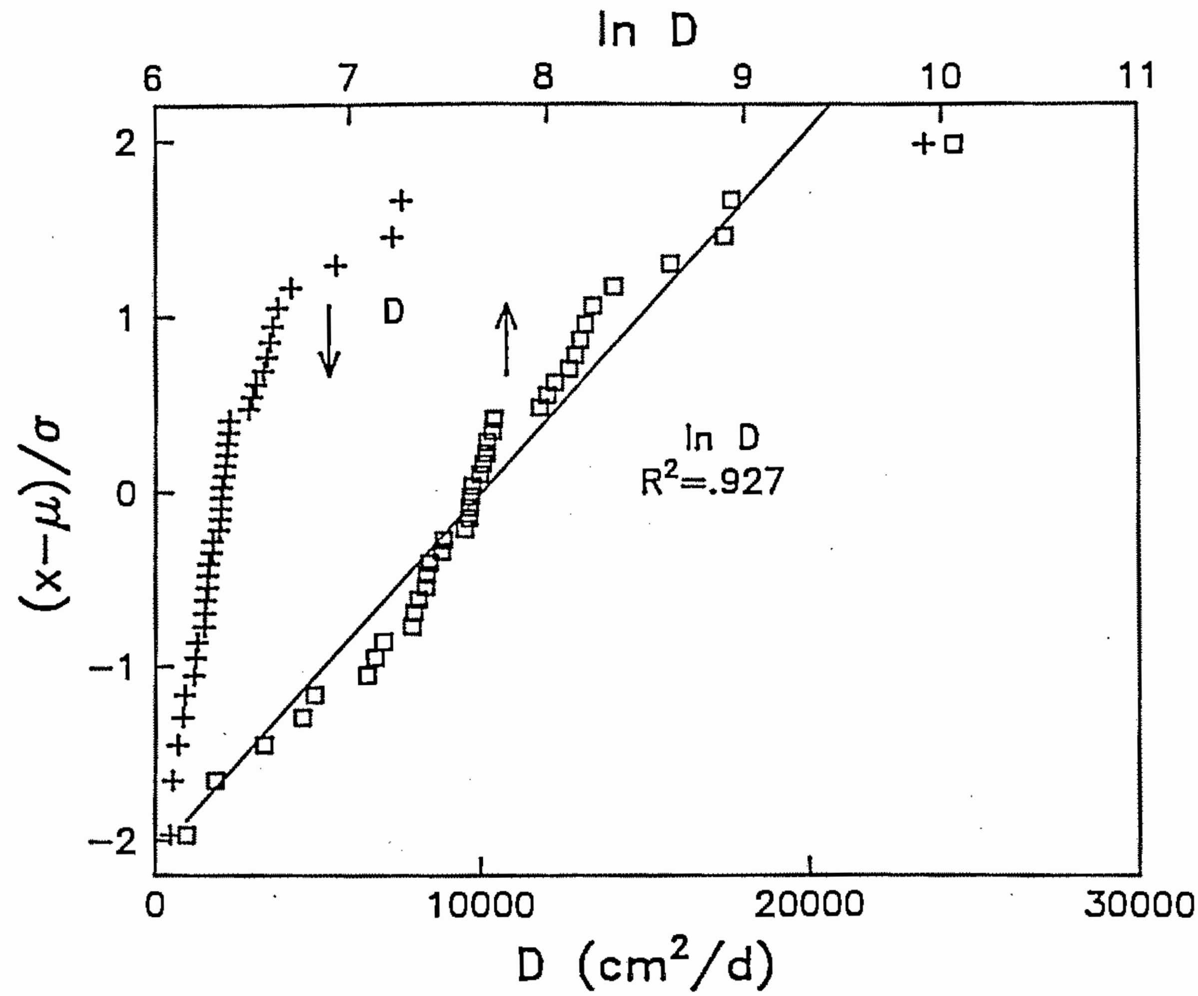

Figure 2. Fractile diagrams for D and ln D fitted to the continuously flooded irrigation results where μ and σ are the mean and standard deviation of the variable x respectively. R^2 values refer to the goodness of fit to a linear relation.

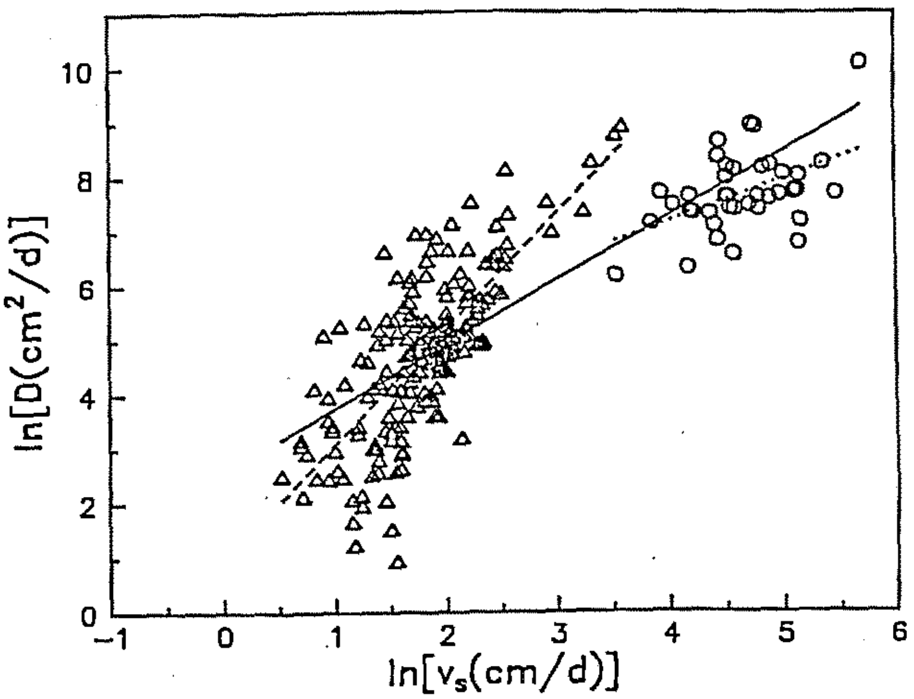

Figure 3. Linear relationships between ln v_s and ln D values fitted to continuously flooded irrigation results (circles and dotted line), dosed irrigation (triangles and broken line) and all the data combined (solid line). Straight lines are the least-square linear regressions to the data. Dosed irrigation data were reported by Bowman and Rice in the 1984 Annual Report.

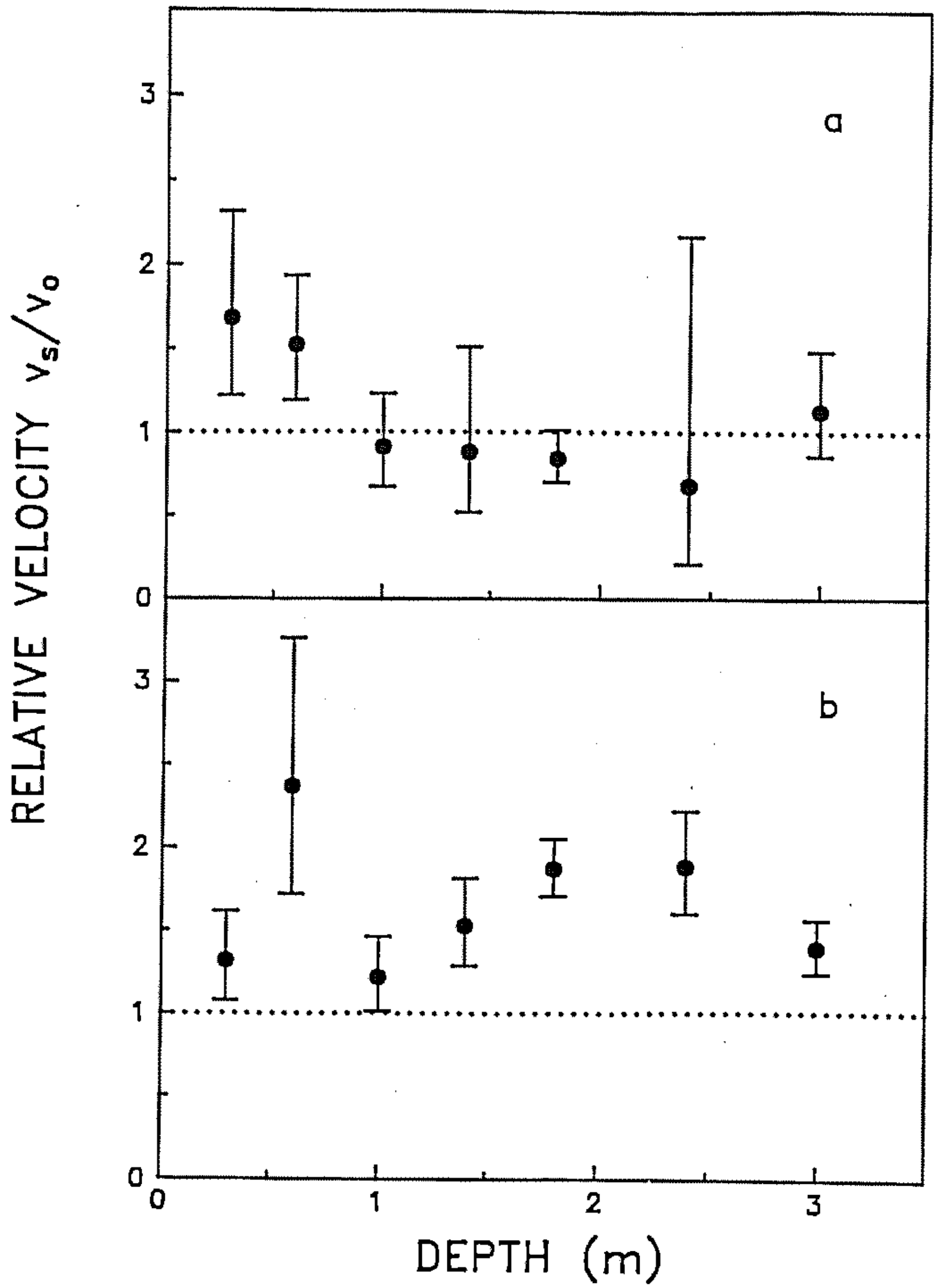

Figure 4. Relative velocities, v_s/v_o, of Br^- versus depth from surface of solution sampler. Points represent mean values, and error bars include the approximate 95% confidence limits for each depth assuming a log-normal distribution. Dotted line defines the 1 to 1 ratio that is expected if no soil water is bypassed. a) Results from continuously flooded irrigation. b) Combined results from all dosed irrigations described by Bowman and Rice.

TITLE: WATER FLOW AND CHEMICAL RETARDATION IN SOILS: A SIMPLE EFFECTIVE LABORATORY DEMONSTRATION

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-20790-005

INTRODUCTION

An appreciation of miscible displacement phenomena is central to understanding water and chemical movement in soils. Leaching of fertilizer nutrients, salts, and pesticides is controlled by water movement through soil, and by chemical interactions between solutes and the soil matrix. Given current awareness and concern over agricultural impacts on groundwater quality, students as well as the general public are very interested in understanding how water and chemicals move downward from the soil surface.

We have developed a simple vivid laboratory demonstration which illustrates principles of miscible displacement and chemical retardation in soils. The demonstration consists of the separation of a mixture of two brightly colored dyes as they pass through a sand column. One dye is strongly retained in the top portion of the column, while the other dye moves unretarded with the percolating water. We have used this demonstration extensively to illustrate these principles to varied audiences ranging from high school students to professional soil scientists and hydrologists. The demonstration lends itself to supporting different levels of discussion depending upon the sophistication of the audience. The time required for the demonstration is 11 to 13 minutes.

MATERIALS AND METHODS

Sand column preparation

The column consists of sand packed in a clear 4.5-cm i.d., 26-cm long plexiglass tube. One end of the tube is plugged with a no. 10 rubber stopper, into which a piece of glass tubing (0.5 cm i.d., 9 cm long) is inserted as a drain. A small piece of glass wool, inserted at the top of the drain tube, and a 4.3-cm disk of 200-mesh screen (ATM Test Sieves, Milwaukee, WI) above the stopper prevent sand from coming out of the drain. Air-dry fine mortar sand is used as the column packing. Other sands or soils can be used, but this will alter the volumes of dye and time required for the demonstration. Portions of sand are added in approximately 3-cm depth increments and packed by tamping with a 2.5-cm diameter aluminum rod. We found that tamping with a large-diameter rod such as this is necessary to prevent "fingering" of added solution down the sides of the column. Sand addition with tamping is continued until the sand depth is 16 cm. total weight of sand required is 420 g. A 4.3-cm disk of 200-mesh screen is placed on top of the sand. The top screen minimizes agitation of the sand when solution is added to the column.

The sand is pre-wet by carefully adding (so as not to disturb the surface) 300 mL of 0.01 M $CaCl_2$ solution to the column and allowing it to drain. If necessary the sand surface and screen are releveled. If the drainage is cloudy, an additional rinse of 30 mL of $CaCl_2$ solution is added. After draining, the column can be used immediately or can be stored wet for several days prior to use.

For the demonstration the column is supported vertically by a ringstand/-clamp assembly. A backdrop constructed of white poster board improves the visibility of the dyes.

Dye preparation

Two grams of Rhodamine B (J. T. Baker no. U872-2) is dissolved in 100 mL of boiling 0.01 M $CaCl_2$ and diluted to a volume of 1 L with 0.01 M $CaCl_2$. Rhodamine B is a brilliant violet dye which is strongly sorbed by soil and sand. Twenty-five grams of reagent-grade potassium chromate, K_2CrO_4 (Mallinckrodt no. 6870), is dissolved in 1 L of 0.01 M $CaCl_2$. CrO_4^{2-} in solution has an intense yellow color, and is not retained by the sand. The solutions described provide enough material for 20 demonstrations, and have a shelf life of at least several years at room temperature.

Demonstration

Fifty mL of Rhodamine B solution is combined with 50 mL of K_2CrO_4 solution in a 125-mL Erlenmeyer flask resulting in a dark-violet solution. This solution is slowly poured onto the sand column while avoiding disturbance of the sand surface. The solution is allowed to percolate through the column with the outflow collected in a clean 125-mL Erlenmeyer flask.

RESULTS AND DISCUSSION

Immediately after adding the dye solution to the top of the column, clear water begins to drip out of the drain tube as the incoming solution displaces water already present (stored) in the sand (Fig. 1a). After about eight minutes, the drainage acquires a noticeably yellow tinge (Fig. 1b). After nine minutes the drainage has the intense yellow color of the original $CrO_4$12⁻ solution. Drainage ceases after 11 to 13 minutes. Sorption of Rhodamine B by the sand results in a bright purple band in the top one-quarter to one-third of the column (Fig. 1c). Further additions of $CaCl_2$ solution will result in the eventual appearance of Rhodamine B in the drainage water.

We have found that our laboratory tap water (electrical conductivity 0.85 dSm^{-1}, primary salt NaCl) serves as well as 0.01 M $CaCl_2$ for dye preparation and column wetting. Use of low-conductivity water (such as distilled water) results in dispersion of fine particles within the column and reduced hydraulic conductivity. This causes the entire demonstration to take more time; for example, CrO_4^{2-} breakthrough occurs after about 16 minutes when distilled water is used rather than 0.01 M $CaCl_2$.

The demonstration illustrates several basic concepts of miscible displacement and soil-solute interactions. The clear water which initially drips out the bottom of the column shows how incoming water at the soil surface displaces and pushes downward water already present within the soil profile. The dilute CrO_4^{2-} leachate which follows the clear water illustrates the mixing due to molecular diffusion and mechanical dispersion which occurs in a porous medium when one solution displaces another.

The more intense CrO_4^{2-} solution which drains next represents the bulk of the volume of the dye slug which was added to the column. The CrO_4^{2-} behavior is analogous to that of NO_3^- and Cl^-, which likewise are not retarded in their movement in most soils. The relatively rapid movement of the anion shows why NO_3^- is often the first pollutant, derived from agricultural use, detected in groundwater.

The Rhodamine B illustrates the behavior of strongly sorbed solutes such as many pesticides, heavy metals, and some fertilizer elements. It shows how arrival of these types of solutes at the groundwater can be greatly retarded relative to percolating water or more mobile solutes.

PERSONNEL

R. S. Bowman, D. B. Jaynes, G. C. Auer, R. C. Rice, and H. Y. Cho

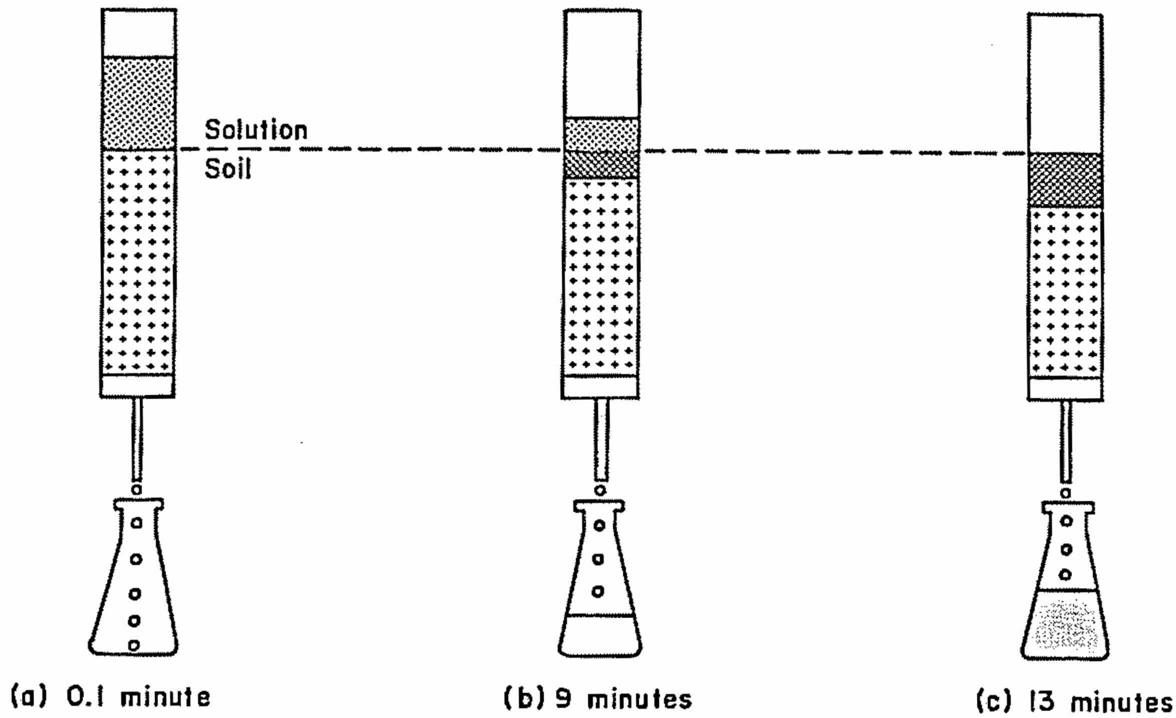

Figure 1. Progression of water and dye through the column as a function of time. (a) Clear solution drips from column immediately after dye mixture is added. (b) CrO_4^{2-} solution reaches bottom of column and begins to drain. (c) Drainage ceases, leaving a dark purple band of Rhodamine B sorbed to upper portion of column.

APPENDIX

LIST OF 1987 PUBLICATIONS AND MANSUCRIPTS PREPARED

ALEXANDER, W. L., BUCKS, D. A., and BACKHAUS, R. A. Irrigation water management for guar seed production. Agron. J. (in progress)(ms #1267)

ALLEN, S. G., IDSO, S. B., KIMBALL, B. A. and ANDERSON. M. G. Relationship between growth rate and net photosynthesis of Azolla in ambient and elevated CO_2 concentration. Agric. Ecosys. Environ. (in press)(ms#1278)

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ALLEN, S. G. and NAKAYAMA, F. S. 1987. DCPTA bioregulation of growth and rubber production of several Parthenium species. Proc. of the 7th Ann. Conf. of the Guayule Rubber Society, Inc., Annapolis, MD 2-6 November 1987. (published) ABSTRACT

ALLEN, S. G. and NAKAYAMA, F. S. 1987. Relation between crop water stress index and plant water status of guayule. Proc. of the 7th Ann. Conf. of the Guayule Rubber Society, Inc., Annapolis, MD, 2-6 Nov 1987. (published) ABSTRACT

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BEAUMONT, J.A. and CLEMMENS, A.J. Flume measures ultra-wide discharge range. Proc., ASCE Hyd. Div., Spec. Conf., Aug. (published)(ms #1299)

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BOISSARD, P., GUYOT, G. and JACKSON, R. D. Factors affecting the radiative temperature of a vegetative canopy. Remote Sensing Reviews. (in press)(ms #1101)

BOUWER, H. Agricultural chemicals and groundwater quality--A look ahead. Proc. Natl. Meet. on Toxic Substances in Agric. Water Supply & Drain.--Searching for Solutions, Las Vegas, NV, 3-4 Dec 1987.(in press)(ms #1369)

BOUWER, H. 1987. Effect of irrigated agriculture on groundwater. J. Irrig. & Drain. Engr. 113(1):4-15. (published)(ms #927)

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